VOLUME XXXV NUMBER 8

THE
JOURNAL OF GEOLOGY

November-December 1927

NOTES ON THE PERMO-CARBONIFEROUS REPTILE DIMETRODON

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ABSTRACT

1. A nearly complete postcranial skeleton of the Permo-Carboniferous reptile *Dimetrodon* is described and figured. The structure and possible function of the spines are discussed, and a mechanical explanation for their origin is suggested. The specimen shows *Dimetrodon* to have been a long-tailed form. The skeleton is restored and a life-restoration given.
2. Models of the probable musculature of the limbs of *Dimetrodon* are presented.

I. A NEARLY COMPLETE POSTCRANIAL SKELETON OF DIMETRODON DOLLOVIANUS (?)

Although the long-spined pelycosaur *Dimetrodon* is without question the most common animal of the Texas redbeds, its fragmentary remains constituting the most common find of the collector in that field, associated skeletons are extremely rare. The specimen described below (No. 1322, Walker Museum) merits description as perhaps the most perfect postcranial skeleton yet discovered. It was found by Mr. Paul C. Miller in one corner of the Craddock Bonebed (Lower Clear Fork) and has been mounted as a slab without any alteration of the position of the skeletal elements and without any restoration except for part of one spine, as indicated by cross-hatching (Figs. 1 and 2).

The animal appears to have been stranded after death in a body of water whose current flowed over the cadaver (which lies upon its left side) from a ventral and anterior direction. This appears to have resulted not only in swinging the anterior limb backward parallel to the body, but also in forcing the backbone into an unnatural curvature; this finally caused a sharp break between the eleventh and twelfth vertebrae. This general recurved position is a common one in vertebrate specimens from fluviatile deposits; in this case, at least, there can be no possibility of the opisthotony which

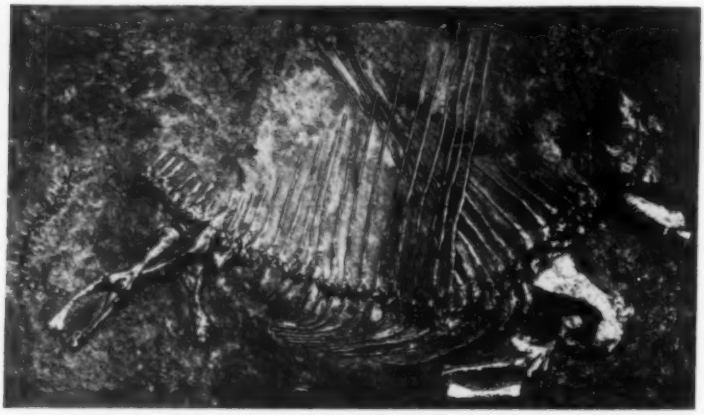

FIG. 1.—Skeleton of *Dimetrodon dollovianus* (?) mounted in the original position (No. 1322, Walker Museum). $\times \frac{1}{15}$.

Moodie[1] suggests as an explanation of the position of many such specimens.

Skull.—This appears to have been disarticulated and broken before burial. The occipit, much of the right maxilla and premaxilla, and several poorer fragments which are preserved agree well in size with similar parts of a well-preserved skull from the same bonebed (No. 40, Walker Museum), and this has been utilized for purposes of restoration.

Trunk vertebrae.—Except for the atlas, the complete series of twenty-seven presacral and three sacral vertebrae is present. Most

[1] *Science*, n. s., Vol. L (1919), pp. 275–76, etc.

of the centra are still contained within the matrix; those exposed do not call for special comment.[1] No intercentra were found in the regions exposed; they appear to have been cartilagenous. The first nine transverse processes are incomplete, but a number of the more posterior ones are well preserved. As is typical of *Dimetrodon*, the more anterior processes are directed sharply backward and downward; by the tenth they point more nearly straight laterally, and the shorter posterior ones even tend slightly anteriorly. That of the

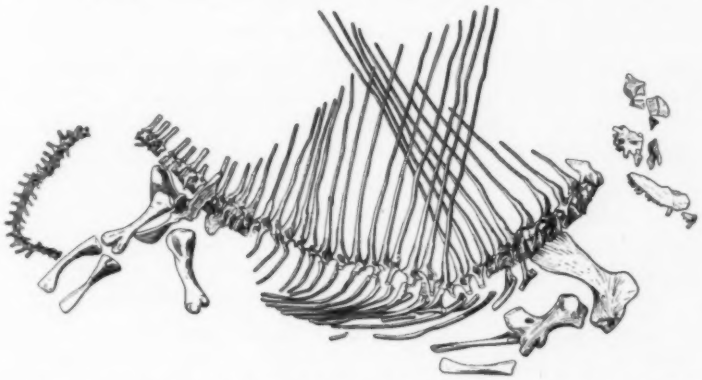

FIG. 2.—Line drawing of the skeleton to show detail. One spine (hatched) is partially restored. $\times \frac{1}{12}$.

tenth vertebra extends 6 cm. from the mid line; that on No. 13, 5 cm.; No. 18, 4.2 cm.; No. 22, 3.3 cm.

Since the centra are buried in so many cases, the vertebral lengths have been taken between the centers of the articular surfaces of the anterior and posterior zygapophyses. Measured in this way, the lengths of the second to thirtieth vertebrae are: 47, 42, 42, 43, 43, 41, 42, 37, 36, 36, 38, 42, 40, 34, 29+, 27+, 37, 36, 37, 36, 31, 27, 28, 32, 29, 29, 29, 22, and 29 mm. This gives a length of about 1.04 meters for the presacrals and sacrals, and an estimated

[1] For the general anatomy of *Dimetrodon*, see Case, "Revision of the Pelycosauria." *Carnegie Inst. of Washington, Pub. 55* (1907); "A Mounted Skeleton of *Dimetrodon incisivus* Cope, in the University of Michigan," *Amer. Jour. Sci.*, Vol. XL (1915), pp. 474–78, etc.; and Gilmore, "A Mounted Skeleton of *Dimetrodon Gigas*," *Proc. U.S. Nat. Mus. 56* (1919), pp. 525–39.

length of about 1.31 meters from the snout to the base of the tail. In general there is a steady decrease from an average of 42 mm. in the cervical to 30 mm. in the lumbar region.

Ribs.—Most of the ribs of the right side are present but disarticulated and with their distal ends displaced posteriorly. They agree in shape and general characters with those of *D. gigas* as described by Gilmore. The complete ribs, as that writer has noted, are cupped distally, indicating a cartilagenous continuation.

The first six ribs are missing, and of the seventh and eighth only the proximal ends are found. The remaining ones are complete except that portions of the tenth are missing and the twentieth to the twenty-second are slightly imperfect distally. In a number of cases the capitulum is concealed by matrix. From the ninth to the twenty-fifth the lengths, measured from the tuberculum, are: 31.4, 31(?), 31, 30, 28.5, 28.3, 27.4, 27, 26, 24, 21.5, 13.3+, 14.4+, 14+, 14.9, 11.6, and 8.5 cm. To and including the twenty-second the ribs are free; the more posterior ones are united to the transverse processes, although the sutural lines are apparent.

The sacrals are well known from previous descriptions. All of the seven proximal caudals preserved appear to have borne ribs fused to the transverse processes, although the ribs are not well preserved. That of the second caudal, which is nearly complete, measures 2.8 cm. from the end of the transverse process, and 4 cm. from the midline. There are no ribs on the posterior caudal series; in *Clepsydrops natalis* the ribs stop at the tenth caudal, and the condition here seems to have been approximately the same.

The spread from capitulum to tuberculum is 4 cm. on the seventh, 5 cm. on the twelfth, and 3.17 on the fourteenth rib. The ribs are about four-fifths of the length of the corresponding ones in Gilmore's specimen of *D. gigas*.

Figure 3 is an attempt to represent diagrammatically the body cross-section in the region of selected vertebrae, as controlled by the position of the ribs when placed in their proper articulations. Although there is considerable opportunity for error, the general contour is probably not far from correct, and is similar to that noted by Gilmore in *D. gigas* (see his Fig. 1, Plate 12, etc.). The body was deep and narrow, with nearly vertical sides. The rib measurements

agree well with an estimated maximum width between the scapulae of 180 cm. The curvature of the more posterior ribs (cf. Case's "Revision," Plate 12) suggests the presence of a narrow "lumbar" region with a V-shaped ventral contour, in harmony with the narrow pubic portion of the *Dimetrodon* pelvis.

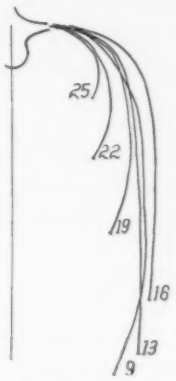

FIG. 3.—Diagrammatic cross-section of the trunk of *Diometrodon* to show the contour of the body in the neighborhood of selected vertebrae (ribs numbered). ×½.

Spines.—The preservation of the neural spines is excellent. With the exception of No. 16, all are complete or nearly so, and there are few breaks or major distortions of any sort. They are arranged in two series, Nos. 2–11 being directed somewhat backward and parallel to one another while those of the more posterior series overlap and cross them superficially at a sharp angle.

The position of the spines in this specimen testifies strongly to the more probable theory of the superficial appearance of the dorsal region of the creature—namely that the spines were covered by a continuous, although probably rather thin, sheath or "sail" of membrane containing connective tissue, ligaments, and probably a small amount of muscle as contrasted with the suggestion (of Abel and especially Jaekel) that the spines formed independent projections. If the spines were separate, the backward curvature of the body in this specimen would have tended to crowd them together at their apices, like the spokes of a wheel. No such result has taken place. Within the two series all of the spines have retained almost exactly the even spacing which they presumably had in life, except that the posterior members of the anterior series are slightly crowded, probably owing to the additional pressure here of the river bar on which the cadaver appears to have been stranded. When the break came—presumably tearing the membrane—the posterior series appears to have passed forward over the anterior one without interference or breaking of any of the spines, a feat which appears improbable in the absence of a connecting membrane.

As noted above, spine 16 is imperfect, and, as seen in restoration

Nos. 12 and 13 appear to be slightly incomplete distally. From the axis to the third sacral, the lengths, measured from the level of the zygapophyses (since in most cases the centra are concealed) are, in order, 63, 130, 195, 322, 401, 531, 579, 609, 660, 678, 619+, 624+, 610, 574, 214+, 538, 495, 478, 413, 375, 340, 319, 284, 232, 174, 130, 107, 95, and 89 mm.

At a point about 6–8 cm. up the spine in the more anterior and posterior members of the trunk series a well-marked diminution in the anterio-posterior thickness of the spines (although not in their width) is evident. As Case[1] and Von Huene[2] have suggested, this point corresponds to the top of the "normal" spine of other pelycosaurs (or of the caudal spines of *Dimetrodon*) and probably indicates the upper limit of the usual longitudinal dorsal musculature. This distinction is less clear in the mid-dorsal region.

The proximal portions of the spines are nearly square in section, although grooved on anterior and posterior surfaces, much as described by Case in the neotype of *D. dollovianus* from a similar horizon (Lower Clear Fork). Distally the spines have the common "dumb-bell" shaped section, broad, but thin antero-posteriorly, with deep grooves on the anterior and posterior surfaces. Von Huene has suggested that these grooves were for the blood vessels, and that this is the case is rendered extremely probable by a fragment of a spine of *Edaphosaurus* in our collections (the grooving is similar in the two genera). Here a branch of one groove turns in a spiral fashion around the side of the spine and joins that of the opposite side; this is obviously a venous anastimosis. Further evidence is offered by the fact that the lower portions of the spines of *Dimetrodon* are often ungrooved; up to the point of constriction mentioned above, the blood vessels would pass upward between the two sets of dorsal muscles, while beyond this, they would be protected in the anterior and posterior grooves; laterally to them were probably attached the ligaments beneath their cutaneous covering.

As nearly as I have been able to restore them in Figure 4, the spines were for the most part nearly vertical in position, although it would seem that the more posterior long spines were tilted slightly

[1] "Revision," p. 116.

[2] *Jahresheft der Verein. f. Vaterl. Naturk. in Württemberg 75* (1919), pp. 177–82.

backward. There is little of the "crumpled" arrangement of the posterior spines seen in *Edaphosaurus*, in which it would appear that a lack of expansion in the posterior portion of the membrane during growth stages causes the distal ends of the presacral spines to be turned backward. The more anterior spines slant slightly forward as well as upward near their bases and then, above, assume a vertical position; the process is reversed in the more posterior members. There is a sharp increase in height from the axis to the seventh vertebra, a slower increase to the eleventh, a gradual decrease to the "lumbar" region, followed by an abrupt drop over the sacrum.

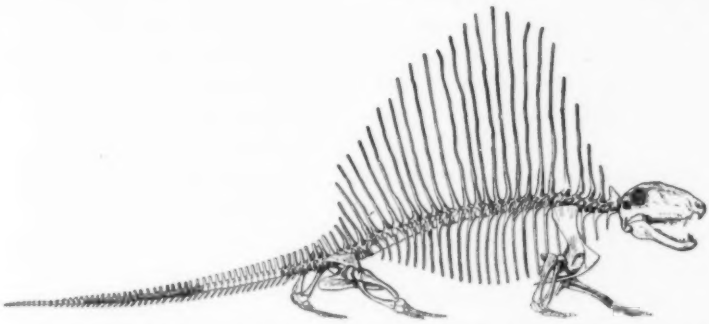

FIG. 4.—Skeletal restoration of the specimen described. The skull is restored from No. 40, Walker Museum. Other parts not present in the specimen are unshaded. $\times\frac{1}{24}$.

If the position of the spines shown here be compared with restorations of other specimens, a number of differences in shape and position will be noted. Some of these differences are quite possibly of a specific character, but a consideration of them seems inadvisable in the present state of our knowledge.

The possible function of the spines of *Dimetrodon* and *Edaphosaurus* has been repeatedly discussed. At first sight they would seem a protective device, but (since Jaekel's idea of a sideways spread is out of the question anatomically) they would protect only from an attack from above, a feat impossible of attainment by any member of their fauna. Further, as regards *Dimetrodon*, the animals themselves are the largest aggressive carnivores of the

time; they are the attackers, not the attacked. Suggestions with regard to visual effects need hardly be considered, while on the other hand Case[1] has rightly emphasized the enormous demands upon the animal's vitality which the development and maintenance of these structures must have made. It is only natural that an appeal has been made to "spinescence" or "racial senility" for an explanation. It is true that *Dimetrodon* has left no descendants, but the same may be said for almost every member of this fauna, spinescent or not, and it is of interest that *Dimetrodon* is the commonest animal from the bottom to the top of the bone-bearing redbeds. If *Dimetrodon* is senescent, racial decrepitude would appear to be a blessing.

While the writer has no adequate explanation to offer for the full development of the spines of *Dimetrodon*, a suggestion may be made regarding their origin and partial development and for a function which may have partially atoned for their injurious effects even when of maximum size—the function of bodily support.

If we survey the degree of development of neural spines in redbeds reptiles, two facts become immediately apparent.

1. Among animals of similar build, the development of neural spines is roughly proportional to size. Among the cotylosaurs, for example, the smaller forms, as *Seymouria* and *Captorhinus* have short neural spines; in the larger forms, as *Diadectes* and *Limnoscelis*, they are proportionately longer. Among the pelycosaurs the long-spined forms are the largest members of the group.

2. Among animals of similar size, the development of spines is roughly proportional to the length and slimness of the body and the presumed activity of the animal. For example, the cotylosaur *Captorhinus* and the pelycosaur *Varanops* are not dissimilar in size; but in the latter (with longer spines) the body is much longer and slimmer and the activity and speed of the animal presumably considerably greater. A similar contrast can be made between a large cotylosaur, such as *Diadectes*, with spines of moderate size, and a large pelycosaur, such as *Dimetrodon*.

Dimetrodon and *Edaphosaurus* are two of the largest and most slimly built forms in this fauna, and it seems impossible to escape

[1] "The Permo-Carboniferous Beds of North America and Their Vertebrate Fauna," *Carnegie Inst. Washington Pub. 207* (1915), p. 142, etc.

the conclusion that their "spinescence" is in some way connected with these facts.

It is only rarely that similar spinous development is found among later vertebrates. But it will be noted that the vertebral column of the early vertebrates was a comparatively weak affair, as evinced by the deeply biconcave vertebral bodies, with a consequent lack of strength in the series of centra. An increase in size and slenderness would tax the strength of the column very considerably, but this strain would be greatly relieved by an increase in development of neural spines. It is well known that in vertebrates generally the spines afford an origin and insertion for the dorsal musculature. These muscles are of great aid in the maintenance of the proper position of the backbone, as, for instance, the curvature of the back between the anterior and posterior limbs. The weight of the thoracic and abdominal viscera tends to pull down the vertebrae at the top of the the arch and flatten it. This would result in a crowding together of the neural arches in this region, naturally accompanied by an increase in distance between the more anterior and posterior spines. This, however, is resisted by the ligament and muscles connecting them, and the proper curvature is maintained. The general effect of the system is that of a truss bridge, with the arches acting as vertical members and the ligaments and muscles as diagonals; the two piers are the limbs.

A weak type of backbone, coupled with increased size, greater activity and a long slim body seem to have been the factors which have been associated with the overemphasis of this truss and the initiation, at least, of the "spinescence" of *Dimetrodon* and *Edaphosaurus*.

It will be noted that in both long-spined forms the great increase in height anteriorly occurs in the region of the anterior limb, while there is an abrupt decrease above the posterior limb. The truss stops at its two piers.

It must be emphasized that this explanation has to do merely with the initiation and the partial development of the spine system. It seems impossible that the total development can serve such a purpose. Here, perhaps, it may be necessary to call upon some type of orthogenetic hypothesis.

Caudal vertebrae.—Seven caudals in series follow the sacrals. The proximal caudals of *Dimetrodon* are well known, and those present here need not be described in detail. The heights from the central line to the tip of the spine are, in order, 65+, 95, 70+, 87, 82, 82, and 84 mm. The lengths are 28, 27, 28, 25, 22, 21, and 18 mm., showing a rapid decrease in the proximal caudal region, as noted by Case. The base of a chevron is present between the fifth and sixth vertebrae; a nearly complete one between the sixth and seventh, in the position of the first chevron of *Clepsydrops*.

Except for scattered elements, the tail of *Dimetrodon* has not been known beyond the eleventh caudal. *Dimetrodon* has usually been regarded as a short-tailed form in contrast to the closely related *Clepsydrops*, and Case[1] has reasonably argued for this point of view from the fact that the proximal caudals decrease rapidly in size. Unfortunately, in our oldest vertebrates, our most reasonable suppositions usually prove to be incorrect; and the present instance is no exception. Following an apparently long break the present specimen exhibits twenty caudal vertebrae in succession, and the more distal members of the series suggest that a considerable length of tail was still to follow.

The centra in this series are long and slender, as is the case in the tail of *Clepsydrops* from the thirteenth or fourteenth on. As would be expected, no traces of ribs are found. The chevrons are usually incomplete, but would appear to have been present throughout. The vertebral lengths (measured on the centra) are 21, 22, 20, 21, 23, 24, 22, 20, 21, 22, 20, 21, 19, 20, 20, 20, 18, 18, and 17 mm., showing a slight general decrease at the posterior end of the series. The heights from the ventral line of the centra to the zygapophyses are 24, 22, 21, 20, 18, 18, 18, 17, 17, 17, 16, 16, 15, 14, 14, 13, 12, 13, 12, and 12 mm.; to the tops of the neural spines, as preserved on the third to seventeenth of the series, 52, 50, 49, 43, 40, 41, 40, 36, 38, 34, 39, 33, 35, 34, and 35 mm. These figures show a steady decrease.

Several estimates based on the measurements suggest that from twelve to fifteen vertebrae are missing between the proximal caudals and this series, which hence includes about the twenty-first to forti-

[1] "Revision," pp. 111, 115, 120, etc.

eth caudal vertebrae. In the series there is a marked decrease in height, but there is little diminution of length and the spines are still well developed at the posterior end, rendering it probable, from comparison with other pelycosaurs, that the total number of the caudals may have reached well over 50.

Appendicular skeleton.—Portions present and exposed include the right scapula and anterior coracoid, the right half of the pelvic girdle, all propodials and epipodials of the right side, and the left femur. The lengths of the limb bones are: humerus, 17.6 cm., radius 16.6 cm., ulna 19.2 cm., femur 19.4 cm., tibia 18.3 cm., and fibula 19.2 cm.

Skeletal restoration (Fig. 4).—Because of the relative completeness of the postcranial skeleton, a restoration has been attempted. The skull is added from No. 40, Walker Museum, which is from the same locality and, as far as can be determined, of identical size and characteristics. All other parts not present in this specimen are distinguished in the figure by an absence of shading; these include part of the tail, the anterior ribs, the dermal shoulder girdle, the manus and pes, and a few missing fragments elsewhere.

Certain difficulties in reconstruction have been encountered. The curvature of the vertebral column is difficult to ascertain; it is of especial importance here because of its influence upon the position of the spines. The position shown was reached after a study of the centra, zygapophyses, and spines, and their mutual relations. It is possible that the upward tilt just anterior to the pelvis should be somewhat lessened. The evidence seemed to point to a curvature, with a concavity below, in the region of the eighteenth to twentieth vertebrae, and a somewhat greater curvature of similar form in the region of the eighth to tenth. It is impossible in this specimen to raise the anterior end of the column, as Gilmore has done in *D. gigas*, without crowding and overlapping of the anterior spines, which are not at all distorted. Spines 11 and 12, adjacent to the break, have been corrected for an apparent postmortem curvature distally; otherwise the spines are an exact copy of the original.

Dimetrodon is customarily restored or mounted with the limbs directed straight outward, a neutral position, and one which was probably assumed in a standing pose. I have, however, attempted

to illustrate the creature in motion, with the entailment of problems which are not entirely solved.

As to the succession of limb motion, Gregory[1] suggests that there was a somewhat sinuous motion of the body, with the advancing limb just in front of a convexity or behind a concavity, and vice versa, resulting in the type of pose illustrated. In the figure the writer has not attempted to take into account the probable rocking motion of the body with a tilt ventrally toward the side of the limb being retired; but the mean elevation of the girdles above the ground given in the figure seems consistent with the result of study of the limb elements in various positions, although the matter is somewhat complicated, and there are numerous points at which error may creep in.

The movement of the humerus of primitive tetrapods has been discussed by Watson, the writer, and Miner, perhaps most successfully by the last.[2] The main motion is a fore and aft one in a nearly horizontal plane, but, it would appear, with the humerus more elevated at the posterior end of the "stroke," and accompanied here by a flexion at the elbow. This would give approximately the motion indicated. It is possible that the extended position shown in the left "arm" is somewhat too great.

Students of these forms have paid little attention to the probable motion of the posterior limb. The acetabulum indicates a considerable rotation of the femur about its main axis, a feature which might have been predicted from the lack of any appreciable possibility of rotation at the knee. As Gregory[3] has noted, it is probable that the mean position of the femur was one in which its distal end was somewhat posterior and dorsal to the acetabulum as seen in side view; but it appears probable that it could be advanced and depressed to about the position shown.

Measurements of the limb bones in various positions suggest a width of the trackway of about 40 cm., and a distance between two

[1] Gregory and Camp, "Studies in Comparative Myology and Osteology, No. III," *Bull. Amer. Mus. Nat. Hist. 38* (1918), pp. 515–17.

[2] "The Pectoral Limb of Eryops and Other Primitive Tetrapods," *Bull. Amer. Mus. Nat. Hist. 51* (1925), pp. 165–68.

[3] *Op. cit.*, p. 532.

positions of the same foot of about 60 cm. when the animal moved rapidly, placing the imprint of the hind foot somewhat in advance of the position of the corresponding front imprint of the preceding cycle.

Life-restoration.—The proof of the presence of a long tail renders a new restoration imperative, and Mr. Bruce N. Crandall has been so kind as to execute the accompanying drawing (Fig. 5), based on the skeletal restoration just discussed. This differs also from earlier sketches in one further respect. The membrane has previously been pictured as beginning at the bases of the neural arches, and the

FIG. 5.—Life-restoration of the *Dimetrodon* drawn from the preceding by Mr. Bruce N. Crandall. $\times \frac{1}{12}$.

spines have been drawn as though visible for their entire length. But, as noted above, the basal region of the spines was covered by the normal dorsal musculature, and consequently they become visible externally only at a higher level.

Species.—The genus *Dimetrodon* contains a large number of species, many of dubious validity. The present specimen appears to be close to the neotype of *D. dollovianus*, from about the same horizon; but whether this is the same as the type of that species (probably from a lower formation) is uncertain.

II. THE LIMB MUSCULATURE OF DIMETRODON

While the general character of vertebrate skeletal elements is determined by their supporting and articulating functions, the finer

details of their structure are usually developed in relation to the surrounding muscles. The skeleton can be properly understood only if considered in relation to the musculature, and, conversely, much information regarding the muscular system of fossil animals is afforded by the study of the skeleton. With these ideas in view, a series of studies in comparative myology and osteology have been carried out by Dr. W. K. Gregory and his students.[1] The writer has been working more especially on the evolution of reptilian limb musculature as shown in the fossil record, the results of which have been published in various articles. In most instances the restoration of the musculature has been made by drawing the bones, placed in proper articulation, and filling in the muscles between their known origins and insertions. In the case of a Saurischian dinosaur *Tyrannosaurus*, the pelvic muscles were modeled in plasticene on a reduced scale copy of the original skeleton, but no attempt was made to preserve this after illustrations had been made.

The models figured here are, as far as I am aware, the first restorations in three dimensions of the musculature of the limbs of a fossil reptile after a careful consideration of the myological and osteological factors concerned. They were prepared at the request of Dr. W. K. Gregory as a part of a proposed American Museum of Natural History exhibit illustrating the development of limbs in land vertebrates. The actual bones (with the exception of the manus and pes) were first mounted in position, and then the muscles modeled in plastilene. When completed they were cast by the skilful hands of Mr. Otto Falkenbach of the American Museum. The writer has previously published figures which aid in an understanding of the muscular elements concerned.[2]

Figure 6 shows the right anterior limb from a lateral and somewhat dorsal view. From the scapula the scapular portion of the deltoid is seen descending anteriorly, while the clavicular portion runs back from the clavical toward the head of the humerus. These two muscles have been cut so as to expose the scapulohumeralis anterior and supracoracoideus beneath them. The subscapularis is

[1] Gregory, *op. cit.*, pp. 447–49.

[2] "The Locomotor Apparatus of Certain Primitive and Mammal-Like Reptiles," *Bull. Amer. Mus. Nat. Hist.* 46 (1922), plates 27–32, 39–43.

seen emerging from behind the posterior edge of the scapula. Just below is the cut end of the latissimus dorsi, situated between the scapular and coracoid heads of the powerful triceps muscle. The extensors of the forearm originate mainly from the ectepicondyle and supinator process of the humerus. There is little evidence as to the detailed arrangement of the musculature of the manus (and pes

FIG. 6

FIG. 7

FIG. 6.—Model of the musculature of the right anterior limb of the *Dimetrodon* as seen laterally and somewhat dorsally. (Figs. 6, 7, 8, 9 courtesy of the American Museum of Natural History.)

FIG. 7.—The same as Fig. 6, as seen medially and somewhat ventrally.

as well), and they have been restored on a generalized reptilian plan as adapted to the bony structure of *Dimetrodon*.

In Figure 7 the same model is shown in an internal and ventral aspect. The subscapularis is seen running down the inside of the scapula (the ridge beneath is merely a supporting structure in the model; the cavity behind it is at the suture between the two coracoids). Outside the coracoid plate are, in antero-posterior order, the supracoracoideus, biceps, and coracobrachialis. The stem of the

interclavicle and the attached pectoralis have been removed to show the deeper muscles, but the tendon of insertion of the pectoralis may be seen in the angle between supracoracoideus and biceps. Distal to this tendon is the brachioradialis. The forearm flexors cover most of the forearm in this view, while the ventral surface of the "hand" is shown in a separate model, not figured.

FIG. 8

FIG. 9

FIG. 8.—Model of the musculature of the right posterior limb, as seen laterally and dorsally.

FIG. 9.—The same as Fig. 8, as seen medially and ventrally.

Figure 8 is the right posterior limb from a dorsal and somewhat lateral position. At the top the puboischiofemoralis internus is seen to arise on the inner surface of the girdle anteriorly and the ischiotrochantericus posteriorly, while farther back are the cut ends of the powerful coccygeo-femorales. The iliac head of the triceps is seen running in a broad sheet to the head of the tibia, while the ambiens appears at the right. Behind the triceps are the iliofibularis and part of the long flexor series. The various elements of the extensor group occupy the surface of the lower leg.

Figure 9 is a ventral view of the same model. The inner surface is unfinished. At the right are the cut ends of the coccygeo-femorales; at the left a portion of the puboischiofemoralis externus. The puboischiotibialis is shown taking origin from a considerable portion of the ventral surface of the pubo-ischium and extending in a broad sheet to the tibia, covering the deeper thigh muscles. At the left the ambiens is visible; at the right the flexor tibialis externus. Below are the powerful flexors of the lower leg; as with the arm, the ventral musculature of the foot has been separately modeled.

Naturally it is the shortest muscles and those which lie closest to the bones concerning which the osseous elements afford us the most information. And hence it is a matter of regret that it is the most superficial muscles, about which we know least, which are most prominent in these models. However, even with the superficial muscles, the origins and insertions can usually be plotted with fair certainty and, knowing the position of the deeper muscles, their margins can be fairly well determined.

Such restorations serve three main purposes. (1) They afford considerable purely myological information and aid in the interpretation of many skeletal peculiarities. (2) They give us a better appreciation of the locomotor possibilities of the form. (3) They are an aid to the restoration of the animal. All too often in restoring the flesh of fossil vertebrates the musculature has been entirely neglected; and where it has been considered, the creatures have sometimes been endowed with musculature of a type belonging to quite unrelated forms.

GRÜNERITE ROCKS OF THE LAKE SUPERIOR REGION AND THEIR ORIGIN

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ABSTRACT

In a previous paper the chemical composition and the mineralogical properties of the Lake Superior grünerite were dealt with (*American Journal of Science*, Vol. XIV [1927], pp. 150 ff.). The occurrence and origin of this mineral is the subject of the present publication. In the Marquette district sideritic cherts were metamorphosed into grünerite rocks by dioritic intrusives. They contain, in addition to grünerite, magnetite, garnet, and either quartz or calcite. At the contact of uralite diabase in the eastern portion of the area no grünerite rocks, but mica-magnetite schists, were formed.

In the Mesabi range the original rock consisted of chert and the hydro-ferrous silicate greenalite. In the eastern portion of the range, at the gabbro contact, these sediments developed into rocks containing grünerite, fayalite, and magnetite. Ferruginous cherts west of the Mesaba station do not contain any amphibole. The substance regarded as grünerite, cummingtonite, or actinolite is optically micalike, and it is supposed to be the crystallized form of former greenalite. The bearing of these facts on the problem of the metamorphism of the area in question is discussed.

THE MARQUETTE IRON DISTRICT, MICHIGAN

Grünerite rocks are of widespread occurrence in the Marquette iron district of Michigan, but the best and most numerous exposures of the whole area are found on Mount Humboldt. In the woods of this hill there occur many extensive outcrops of grünerite rocks which, on account of their resistance to weathering, form ridges protruding above the adjacent igneous intrusions.

The grünerite rocks may consist almost entirely of grünerite, with only small quantities of calcite and magnetite and a few grains of garnet; but in many places the amount of the latter mineral increases until the rocks are besprinkled, as it were, with pink garnets, either of rounded shape or in dodecahedrons. The microscope shows no double refraction in the garnets, but they contain inclusions of grünerite laths, in some cases so abundantly that they practically fill the host. The principal part of the grünerite occurs in small laths, and it is accompanied by variable amounts of magnetite. Layers rich in magnetite alternate with other layers that contain only a few magnetite crystals. Calcite is an insignificant constituent of the rock, and quartz never has been observed in this variety.

Very common is another rock type of banded appearance. The alternating layers consist of quartz and of grünerite and magnetite. Under the microscope, the quartz appears in grains which are neither interlocking nor strained and crushed. Only a few grünerite laths and magnetite crystals are scattered through this quartz mosaic. Other layers are composed of magnetite with some quartz and a little grünerite, whereas in others predominating grünerite is accompanied by a little quartz and magnetite. In the latter layers garnet is as common as in the first rock type. It must be mentioned that grünerite in many cases is intergrown with blue-green amphibole of lower birefringence and strong pleochroism, resembling that described from Republic.[1]

In a third rock variety from Mount Humboldt, grünerite is altogether absent, and magnetite and quartz, arranged in alternating layers, are the dominant minerals. Minor constituents are muscovite and chlorite (penninite). Occasional brown patches or fibers of higher birefringence within the chlorite suggest remnants of biotite.

The Negaunee iron formation, to which all these rocks belong, strikes in a narrow strip from Mount Humboldt westward toward Champion, Michigan. It forms a ridge of grünerite rocks with igneous intrusions south of the town, and outcrops at the abandoned railroad station of the old Champion mine. The main rock is the banded variety, as characterized previously, and contains quartz, grünerite and magnetite layers, and garnet. Quite a different development is shown in an outcrop near the station. Here the various minerals are not arranged in layers, and each is well individualized. The large crystals of garnet are free from inclusions, with the exception of some chlorite; the grünerite is arranged in rosettes and is partly fresh, partly of a yellowish-brown color, the latter apparently due to oxidation; magnetite appears in large aggregates, and the quartz is coarser here than elsewhere.

Farther west, grünerite schists occur north of Michigamme Lake. A specimen from the Michigamme mine in the petrographic collection of the University of Chicago, according to label and geologic map, belongs to the Ishpeming iron formation (Bijiki schist). The schistosity is well developed. The principal mineral is grünerite.

[1] *American Journal of Science*, Vol. XIV (1927), p. 154.

It occurs in rosettes and is frequently intergrown with a blue-green amphibole, both amphiboles being fresh and unaltered. Magnetite and quartz occur in the same way as at Mount Humboldt. Garnet was not observed.

A specimen of a grünerite-magnetite rock from Republic, Michigan, received from Mr. E. L. Derby, Jr., geologist of the Cleveland Cliffs Iron Company, Ishpeming, shows grünerite and blue-green amphibole in parallel intergrowth. The rock is rich in magnetite, which, in some layers, predominates over the grünerite. Quartz and garnet are absent.

In the broad area of the Negaunee iron formation in the vicinity of Ishpeming-Negaunee, grünerite rocks are much rarer. Only west of the Bellevue Farm (south of Negaunee) do they seem to be somewhat more abundant. These rocks are very fine grained and consist of alternating layers of magnetite and grünerite, without other minerals.

Grünerite rocks are also mentioned as occurring at Lake Bancroft, north of Ishpeming. Although a careful search was made, no grünerite was found in the schists in contact with the greenstone here. In fact, the rocks adjacent to the greenstone knobs in the immediate vicinity of Ishpeming and Negaunee differ considerably from the grünerite rocks, their distinctive feature being this very absence of grünerite. In a grayish green mass with reddish streaks, numerous small octahedra of magnetite are discernible. Schistose and banded structure is common. In thin sections magnetite is dominant. It may be arranged in distinct layers alternating with fine-grained quartz layers and with others that contain magnetite, mica and chlorite, as well as quartz. In other sections these latter two minerals occupy much more space. The mica usually appears in the felted, scaly form of sericite, which, however, occasionally develops into well-individualized muscovite. Rarely remnants of biotite may be seen in the chlorite (penninite). Tourmaline and a mineral with relief and double refraction near apatite, but with positive elongation, were observed. At a short distance from the greenstones these magnetite-mica schists grade into banded hematite-bearing jaspers, and evidently represent a metamorphous phase of the latter. It is noteworthy that these schists are closely related to, if not identical

with, the micaceous variety of magnetite rocks described above from Mount Humboldt.

Geologists agree that the iron ores of the Marquette district and the banded jaspers and ferruginous cherts must be derived from an original sideritic chert. The mining of siderite rocks has developed recently, and there are now good exposures of this rock at the southern boundary of the Negaunee iron formation, northwest of Palmer, Michigan. At the Maitland Mine the banded structure is well developed throughout. Layers of silica and siderite alternate and dip 20° toward the northwest. The silica is no longer chert, but it is fine-grained quartz. Scattered through the siderite are numerous small grains, in many cases octahedra, of magnetite, which may occupy half or more of the section.

The incipient metamorphism of the original sideritic chert, suggested by the abundance of magnetite and by the beginning of the crystallization of silica, is made more conspicuous by the appearance of occasional layers of coarse quartz which contains also biotite, sericite, and chlorite. These layers must have been formerly deposits of a coarse sandstone whose clayey cement was metamorphosed into mica and chlorite.

At the north side of the quarry the siderite is completely altered to hematite, and the rock approaches closely to a banded jasper. It contains, however, an unusual amount of magnetite.

The siderite-magnetite rocks evidently represent the lowest degree of metamorphism in the Marquette district, for in them a part of the siderite was left intact. The second stage is that of the magnetite-mica schists at Negaunee-Ishpeming, where all the iron ore is magnetite and where no amphibole was developed. The third and final stage is represented by the grünerite-magnetite rocks; but they themselves are not uniform. In some of them all of the silica is combined with the iron as amphibole and garnet, whereas in others a part of the silica and iron formed silicates, while the remainder crystallized to quartz and magnetite.

It is here supposed that the grünerite-magnetite rocks must have been derived from original sideritic cherts. This assumption is supported by the following facts: (1) The grünerite-magnetite rocks occupy stratigraphically the horizon of the iron formation, and sideritic

rocks pass in the direction of their strike into grünerite rocks. (2) The banded structure of the original rock is usually well preserved in spite of a high degree of metamorphism. (3) Sideritic, grüneritic, and magnetitic schists have the same chemical composition.

THE CAUSE OF METAMORPHISM

C. R. Van Hise writes, in his "Treatise on Metamorphism": "If any case of metamorphism ought to be called contact metamorphism, the development of the silicated rocks from the iron-bearing carbonates should be so designated, since in the Lake Superior region the presence of igneous rocks seems to have been an essential condition for the process to take place on an extensive scale."[1] These igneous rocks occur, according to Bayley, in the eastern part of the Marquette district, "in the form of knobs and bosses; in the west they are linear in shape and dikelike in their general features." Also the rocks themselves "differ materially."[2] In the vicinity of Ishpeming-Negaunee the knobs consist of uralite diabase with well-preserved ophitic structure. The feldspar, originally basic, is now rather acid, but an exact determination is impossible on account of the numerous inclusions. The low refraction and the extinction angle place it close to $Ab_{95}An_5$. Epidote and chlorite fill the feldspar laths as alteration products. The amphibole is pale-green uralite. Williams[3] saw "cores of red augite in the secondary hornblende" in a specimen from the northern border of the Negaunee iron formation. Epidote occurs through the entire section as an important constituent. Ilmenite, partly altered to leucoxene, is seen in large crystals; pyrite is also present. The interstices are filled with coarse-grained quartz, frequently in micropegmatitic intergrowth with plagioclase.

The rock just described was taken from a knob north of Negaunee. South of this town, at the Gesick Monument, the transition of the granular uralite diabase—here free from quartz—into the schistose form could be well observed. The non-schistose rock contains calcite and more chlorite than the one just described. The plagioclase appears in skeletal forms, and much is replaced by chlorite.

[1] *U.S. Geol. Survey Monograph 47*, p. 840.

[2] W. S. Bayley, in *U.S. Survey Monograph 28*, p. 501.

[3] G. H. Williams, "The Greenstone-Schist Area of Menominee and Marquette Regions of Michigan," *U.S. Geol. Survey Bull. 62* (1890), pp. 174, 175.

Uralite is preserved, whereas in the schistose form it is wholly replaced by chlorite. On the other hand, in this schistose rock the plagioclase is remarkably fresh and of low refraction; it seems to be pure albite. Frequently the laths are broken and the fractures are filled with chlorite. The latter also, as a film, covers the fracture planes of the rock.

The igneous rocks of Mount Humboldt differ considerably from the foregoing uralite diabase. No ophitic structure is observable. The femic mineral is a quite fresh blue-green amphibole with strong pleochroism, c is intensively blue-green, b green and a yellowish. In other instances the core alone is fresh and blue-green, whereas toward the rim the mineral becomes a pale-green, fibrous, and fasciculate aggregate without pleochroism. Twinned albite occurs in large laths. It contains inclusions of chlorite and some amphibole. Portions of the feldspar are replaced by an aggregate of quartz and small grains of hematite. Such aggregates are also found outside of the feldspar and are possibly derived from the iron formation in which the eruptive was intruded. In addition to amphibole, chlorite and biotite are present, and both are in many cases intergrown and unaltered. No mineral of the epidote group occurs.

Thus these rocks differ widely from the uralite diabases of Negaunee. The dark mineral originally was apparently not augite, but amphibole. The primary plagioclase belonged to the acid group; hence neither epidote nor calcite was found as a by-product of its alteration to albite. Biotite, not observed in the diabases, is here always present. Rocks of such a mineral aggregation and of granular structure ought to be classified as *diorites* not as diabases or greenstones.

There occurs also a variety of the same rock in which amphibole prevails over plagioclase. It may be regarded as a differentiation product. Of a lamprophyric character are also those schists which were formerly described as chlorite schists. They consist almost wholly of biotite and chlorite. Both minerals are fresh and of contemporaneous origin, and contain numerous garnets. Some tourmaline was seen. The intrusion in garnetiferous grünerite rocks is plainly visible in a rock ledge not far from the old Mount Humboldt mine. The contact is lined with a layer of garnet and grünerite blades. In

the immediate neighborhood of these schists a more silicic dike is found in the same grünerite rock. It contains very much labradorite (Ab_1An_1) in rounded grains with rare lamellar twinning. This feldspar incloses numerous small hematite grains, and its rim is, as a rule, greatly sericitized. Biotite and chlorite are present in the same form and aggregation as in the above schist. Neither in this dike nor in the schist is there any amphibole.

From these examples it is seen that the igneous rocks of this area are much more variable than heretofore supposed, and that they require further study. However, one fact seems to be evident: They belong to the intrusive facies of the large underlying magma, as is suggested by their occurrence in linear ridges and by their texture. On the other hand, the diabases in the east may have cooled closer to the earth's surface, which well agrees with their appearance in knobs and bosses. This difference then also accounts for the difference in the metamorphism of the iron formation in which they were intruded. In the west, grünerite and garnet, the highest products of metamorphism, were formed, while in the east the formation of micas and chlorite, in addition to magnetite, prevails. Even the siderites are locally preserved. Furthermore, in the west the whole area is metamorphosed. This is due, on the one hand, to the rather acid character of the intruded magma; on the other hand, to the intimate contact of this magma with the iron formation, evidenced by the occurrence of numerous sills and dikes throughout the whole formation. In the east the metamorphism not only is of a lower grade, but is restricted to the immediate neighborhood of the basic greenstone knobs. At a distance of several yards the magnetite rocks, containing mica and chlorite, grade into normal banded jaspers with hematite. This can be well observed at the contact of the diabase knobs northeast of Ishpeming (in the center of Section 2). Observations in Cliffs-Shaft mine, Ishpeming, point in the same direction. At the contact of the greenstones, metamorphosed jaspers were found with magnetite octahedrons, whereas the main mass of the ore is hematite, and even siderite was found in the mine 500 feet below the surface.

In former years the difference in the appearance of the eruptives and the difference in metamorphism of the iron formation were

mainly ascribed to a difference in dynamical influence. According to Bailey, "in the western part of the Marquette district the folding and mashing of the formations were more severe than they were in the Ishpeming-Negaunee area."[1] It seems to be evident that the difference between the eruptives of the west and those of the east must be regarded as primary, i.e., based on a difference in the material which was intruded or extruded. Some after-effects of the intrusion are undoubtedly visible. The uralitization of the augite in the diabase and the alteration of the feldspars to albite in both rocks, and the chloritization of uralite, are processes which require a rather high temperature, and which, therefore, always closely follow intrusion or eruption. But even before these changes took place, the rocks must have differed materially. The original rock in the east was an ophitic diabase which contained, in addition to augite, rather basic plagioclase and ilmenite as important constituents, whereas in the west the rocks were dioritic with green amphibole and biotite as original minerals and with plagioclase so poor in lime that no epidote developed through its alteration to albite.

As regards the metamorphism of the iron formation, it seems to be established that even the greatest dynamic processes cannot form perfectly crystallized grünerite from quartz and siderite, nor form garnet. High temperature is required for such a metamorphism; and it is a fiction of the hypothesis of dynamical metamorphism that sufficient heat might be developed by mountain folding and faulting.

The severity of folding and mashing in the western area is more assumed than observed. It was apparently inferred from the high metamorphism of the iron formation and from the interleaving of the grünerite rocks with the diorites. But this interleaving can be accounted for by the intrusive character of these eruptives. As far as observations go, the folding and faulting in the eastern part was as severe as that in the western. An idea of the severe folding and faulting of the jaspers near Ishpeming may be obtained on examination of the illustrations given by Van Hise.[2] In spite of these extreme disturbances the rock remained jasper, and neither magnetite nor grünerite was developed. As to mashing, attention is called to the

[1] W. S. Bailey, *op. cit.*, p. 501.

[2] *Op. cit.*, Plate 32, A and B, p. 464, and Plate 33, B, p. 466.

fact that even in the highest state of metamorphism, quartz, so responsive to dynamical forces, shows hardly any effect of pressure.

According to Van Hise, "the development of the grünerite-magnetite schists seems to have been favored by deep-seated metasomatic changes" (*op. cit.*, p. 369). Undoubtedly the dioritic intrusions in the grünerite rocks require a certain depth for their slow cooling and for their metamorphosing action. However, a moderate depth would suffice. On the other hand, a metamorphism by "deep-seated" processes presupposes a depression of the Mount Humboldt area by many miles to account for the formation of grünerite and garnet, while at the same time sideritic rocks at Palmer, at a distance of only 12 miles, must have been much closer to the surface, an assumption which in no way is warranted by the stratigraphic position of these rocks and by the tectonic of the formation. The insignificant influence of depth is also illustrated by the fact mentioned before, that in the mine, siderite occurs at a depth of 500 feet, and that, in contact with the diabase at this depth, the same phase of metamorphism occurs as at the surface, namely, that producing magnetite-mica-chlorite schists.

II. THE MESABI RANGE, MINNESOTA

The publications on the iron formation of the Mesabi range give one the impression that amphiboles are widely distributed within this area. Grünerite, cummingtonite, and actinolite are frequently mentioned as occurring in ferruginous cherts (or taconites) all over the Biwabik iron formation. In reality, the occurrence of amphibole is restricted to the eastern portion of the formation in question. This amphibole is partly grünerite, partly an intermediate form between grünerite and actinolite. Cummingtonite was never observed; actinolite, only once.

The westernmost occurrence of grünerite is at a place northeast of the Mesaba station, and its description, by Professor U.S. Grant,[1] is the best of any referring to the Lake Superior grünerites. Grünerite is associated with magnetite and much calcite. "It is supposed to owe its crystalline character to the influence of the great gabbro mass just to the south." Specimen 379 H, which is described by H. N.

[1] Minnesota Geol. Survey, *Geology of Minnesota*, Vol. V (1900), pp. 364, 365.

Winchell in the same volume (p. 923), is evidently from the same locality, but Winchell leaves it doubtful whether the amphibole is grünerite or actinolite. Through the courtesy of Professor F. F. Grout the writer was enabled to examine this specimen as well as the original thin section. The grünerite is typical. The determination of the refractive indices and the extinction angle gave the same values as those found in the Mount Humboldt grünerite.

Grünerite rocks also occur in the vicinity of Birch Lake, at the eastern end of the Mesabi range. Through the kindness of Professor U. S. Grant the writer was permitted to examine characteristic specimens and sections preserved in the collection at Northwestern University.[1] These rocks contain grünerite as a subordinate constituent. The principal minerals are hypersthene, fayalite, magnetite, and quartz. Hypersthene frequently includes small, colorless laths of grünerite, characterized by their high birefringence and polysynthetic twinning. The laths terminate in very fine fibers. Besides the occurrence in the Mesabi range, grünerite rocks, consisting of magnetite, quartz, and fibrous grünerite, also occur in the Gunflint formation, near the international boundary.

An amphibole in a rock taken from Wicks' drill hole, Sec. 27, T. 60–13 W., about 9 miles northeast of Mesaba station and southwest of Iron Lake, was described by N. H. Winchell as grünerite.[2] Later[3] he called the rock "actinolite-magnetite schist." An examination by the writer of the original thin section of this rock showed the amphibole to be undoubtedly near actinolite.

One would expect grünerite rocks in the quarries of Babbitt, Minnesota, a few miles north-northeast of the preceding locality. But neither grünerite nor fayalite is contained in my collection from this place. The magnetite mined there is taken from highly metamorphosed taconites, consisting of alternating layers of coarse-grained quartz, magnetite and amphibole, and, occasionally, of monoclinic pyroxene. The amphibole, as a rule, is of a pale green color with faint pleochroism, a having a yellowish tinge; the extinction

[1] See U. S. Grant, "Contact Metamorphism of a Basic Igneous Rock," *Bull. Geol. Society of America*, Vol. XI (1900), p. 503.

[2] *Geology of Minnesota*, Vol. IV, p. 392.

[3] *Ibid.*, Vol. V, p. 751.

angle on (010) is 14°–15°. There are frequent partings visible along (001). The refractive indices are:

$$\alpha = 1.655 \pm 0.002;\ \beta = 1.668 \pm 0.002;\ \gamma = 1.680 \pm 0.002;$$
$$\text{therefore, } \gamma - \alpha = 0.025 \pm 0.002$$

which agrees with observations in thin sections. The negative optical angle is large, close to 90°.

After the removal of magnetite from a specimen without pyroxene, the mixture of amphibole and quartz was analyzed. Calculating the weight of the oxides into metasilicates, and regarding the remaining SiO_2 as free quartz, the oxides gave the following percentages: 5.3 Al_2O_3, 11.8 Fe_2O_3, 22.4 FeO, 2.8 CaO, 5.4 MgO. I am well aware that such a procedure is objectionable and that the data cannot be definitive. But they give some idea of the relative amounts of bases. The amphibole differs from grünerite in the greater percentages of ferric iron and alumina, and from actinolite and common hornblende by the high amount of iron and the low percentages of lime and magnesia. This and the high refraction give the amphibole an intermediate position. To assign this position more exactly would require a complete analysis of pure material, which is not at hand.

The amphibole shows poikilitic texture with quartz as the included mineral. Other specimens contain monoclinic pyroxene which is yellowish-green under the microscope and is without pleochroism. The extinction angle is at least 40°, but poor cleavage prevents exact measuring. Piercing the pyroxene irregularly occurs some bluish-green amphibole, c being blue-green, b and a yellowish-green. This amphibole is also found in parallel orientation with the faintly pleochroic variety. It is clearly seen that the birefringence of the latter is slightly higher than that of the former.

This is all that is known, at present, about the occurrence of amphiboles in the eastern portion of the iron formation of the Mesabi range. Further field work, based on the present knowledge, will probably yield more important information on the metamorphism of the iron formation of this area, and the writer intends, in the near future, to continue these studies.

It was said that the amphiboles are restricted to the eastern part of the Mesabi iron formation. The line taken as separating the east

from the west is roughly the Allen Junction–Mesaba Railroad. To be more correct, it should be said that, whereas near the Mesaba station grünerite occurs, the ferruginous cherts from the Donora mine, about 5 miles west of the railroad, are free of amphibole; and the same can be affirmed of the taconites thence to Hibbing, Minnesota. Beyond Hibbing the taconites were not examined.

The writer is very much indebted to Professors U. S. Grant, F. F. Grout, and A. N. Winchell, who intrusted to him a number of characteristic specimens and thin sections from all over this area. They are mostly original sections and specimens whose descriptions are given in Volume V of the *Geology of Minnesota* and in *U.S. Geol. Survey Monograph 43*. The specimens and sections of the four "amphibolitic cherts" whose analyses are reported in *Monograph 43* (p. 141), and those ferruginous cherts (or taconites) which contain "plainly actinolite, grünerite, or cummingtonite," and those in which "the amphibole constituent is abundant," or of which microphotographs were given, were particularly examined. The observations are as follows.

One of the most characteristic taconites of this group is specimen 39 S, from west of Biwabik, which is described by N. H. Winchell in *Geology of Minnesota* (Vol. V, pp. 927–29). There are "many roundish, greenish-yellow areas, which are not in crystalline condition (at first), but simply amorphous, isotropic aggregates." But along cracks a change takes place. "This change progresses irregularly, frequently appearing in isolated points in the yellow mass and forming more transparent, finely crystalline nests. These nests multiply and also enlarge, such enlargements taking a radial, or spherulitic structure, thus converting the whole original grain into a finely reticulated and radial network of fine, fibrous, crystalline matter. . . . . As to the nature of these radiating fibers, they are plainly actinolite, or an amphibole allied."

The observations are excellent and accurate, but they fail in the interpretation of the crystallized matter. The optical properties of the fibers or scales are quite different from those of amphibole. The crystallized substance is colorless, and the fibers, if well defined, have always parallel extinction with positive elongation. The birefringence is high, 0.040–0.045. The optical character is negative, and the

axial angle zero or close to zero. There are numerous basal cuts in the section favorable for such observations, and the powder contains many flakes which are perpendicular to the axis (or bisectrix a) and which give in immersion liquids well discernible figures, showing, as a rule, one axis. Cleavage was never seen, but the frequent occurrence of basal fragments suggests a micalike orientation of cleavage, although it must be less perfect. The refractive index γ of the basal flakes is 1.623 ± 0.002. It was impossible to find fibers or flakes exactly parallel to the axis or axial plane. Thus α could not be measured, but, from the birefringence, it must lie between 1.578 and 1.583. Those granules which are still isotropic have a considerably higher index of refraction, namely, 1.676 ± 0.002.

From these optical properties it is certain that the fibers are not amphibole, for the characteristics of amphibole are entirely absent. The crystallized substance is much more micalike, while the scaly-fibrous texture reminds one of sericite. On the other hand, the chemical composition excludes sericite or any other mica. The fibers are obviously a crystallization of the hydro-ferrous silicate greenalite, whose amorphous granules are still partly preserved. The crystallization took place without an appreciable change in composition, as is shown by the agreement of the analyses of greenalite and "amphibolitic" cherts (*Monograph 43*, pp. 108, 141), although some of the water probably escaped in the act of crystallization. At present, therefore, it would be appropriate to call the new product "crystallized greenalite," reserving a special name, eventually, for the future.

A description and an analysis of another specimen (45028) from the same place are given in *Monograph 43* (p. 141). Under the microscope it is seen that the greenalite granules are almost completely crystallized, often with retention of the original shape. The scaly-fibrous mass is colorless and of high birefringence (0.045–0.050). The mineral is uniaxial negative, as a rule, although in one case it showed a small optic angle. Inclined extinction, mentioned in *Monograph 43*, could not be observed in well-defined fibers. Flexuous fibers may have led to such a statement. The exact determination of refractive indices was impossible on account of the small size of the individuals, but it is apparently close to that shown in the former specimen.

As regards the chemical properties, it is stated in *Monograph 43*, *loc. cit.*, that "in strong hydrochloric acid a considerable amount

of the dark material was dissolved out, leaving a white residue." This fact alone should have cautioned against the interpretation of the mineral as amphibole. According to Dana, "most varieties (of amphibole) are unacted upon by acids," and Hintze says: "Durch Säuren sind nur die eisenreichen Varietäten etwas zersetzbar."[1] The amphibole richest in iron is grünerite, yet after boiling the fine powder for more than 4 hours in concentrated hydrochloric acid, the fragments showed no trace of etching. On the other hand, after boiling the powder of the above specimen (45028) for 2 hours in hydrochloric acid, the silicate was completely decomposed and the residue consisted of quartz and amorphus silica. Should the optical properties leave a doubt, the chemical test proves conclusively that the crystallized silicate is not amphibole.

The two preceding specimens were described at some length on account of their paramount importance in the question at issue, and because here the problematic mineral is well developed and unaffected by weathering. While the crystallized greenalite of these two rocks was colorless, it is more or less colored and pleochroic in other specimens. In No. 133 S (*Geology of Minnesota*, Vol. V, p. 932), from about $7\frac{1}{2}$ miles NNE. of Hibbing, the fibers are yellowish in their positive elongation and mostly colorless in the other direction. In a specimen from a place close by (125 S, *ibid.*, p. 932) the sheaves have always perceptible pleochroism; $\mathfrak{c}$ is greenish or yellow, and $\mathfrak{a}$ is almost colorless. In both specimens the pleochroic fibers and sheaves agree optically, except in color, with those described. The optical angle is very small, if not zero, and parallel extinction was well observable. These fibers also, therefore, were incorrectly identified as actinolite.

In a specimen from west of Biwabik (53 S, *ibid.*, p. 929), the greenalite grades from the amorphous state, through aggregate polarization and pleochroic granules, into dark brown individuals of a high pleochroism like biotite. $\mathfrak{c}$ is very dark, almost opaque. The birefringence of the uniaxial negative fibers is high, but an exact determination was impossible on account of the deep color. This also prevents an exact measurement of the indices, but they seem to be a little higher than in the former specimens. N. H. Winchell speaks, with regard to this specimen, of an "actinolitic(?) ingredient" and

[1] C. Hintze, *Handbuch der Mineralogie*, Vol. II, p. 1192.

of a "biotitic substance" (p. 930). It is evident that no amphibole is present. The substance here is also very probably crystallized greenalite, the deep colors being caused by the presence of more ferric iron, either original or from oxidation, than usual. The greenalite granules are themselves partly deep brown, instead of light green.

Other original specimens and sections were examined, among them the analyzed "amphibolitic cherts" 45648 and 45649 (*Monograph 43*, p. 141), and other sections supposed to contain grünerite (*Monograph 43*, p. 117, and Plate XIII, Figs. A and B, p. 128, and Plate XV, Fig. B, p. 132) and specimens in the collection at the Northwestern University from Eveleth and Virginia, Minnesota. The examination confirmed the previous statements. In some cases the poor definition of the substance prevented a determination of the optical properties in the thin section. But hydrochloric acid decided always against grünerite or any other amphibole, the silicate being completely decomposed in a short time.

To sum up: In the taconites of the Mesabi range from west of Mesaba to Hibbing no amphibole could be found. The mineral which was regarded as such is optically micalike, uniaxial, or nearly so, and negative. It has parallel extinction, a maximum index of about 1.62, and, as a rule, a high birefringence up to 0.050. Color and pleochroism are variable. Hydrochloric acid decomposes the mineral readily, as it does also those substances which are badly defined and admit of no optical decision as to their nature.

That is exactly what might be expected. Greenalite is a mineral gel which decays readily. After heating for several hours to 110° C., the green substance becomes red brown by oxidation. Amphibole, on the other hand, forms only at high temperatures, of about 400–500° C. It therefore seems impossible that amorphous greenalite can occur with amphibole. The fibers and scales, mistaken for amphibole, are very probably the crystallized form of the hydro-ferrous silicate greenalite. Such a crystallization seems to take place spontaneously, like the transition of opal to chalcedony, without an appreciable change in chemical composition, but with the loss of some water.

The absence of amphiboles in the western portion of the Mesabi iron formation and its presence in the eastern part has a special bear-

ing on the understanding of the metamorphism of this formation in the latter area. Former geologists have ascribed this metamorphism to the gabbro. A. H. Elftman reached the conclusion: "The nearer the gabbro is approached, the more crystalline is the nature of the rock, until on both sides of Birch Lake it is wholly crystalline."[1] N. H. Winchell remarked: "It is very likely that the presence of the eruptive rock in greater nearness to the ore-bearing localities has been a powerful cause in rendering the ore magnetic."[2] In the *Geology of Minnesota*, Vol. IV (1899), p. 392, the same author says of an amphibolitic rock referred to above: "The rock is apparently a part of the taconite, concentrated and crystallized by the gabbro."

U. S. Grant has treated this problem in detail.[3] "The original rock is regarded as a glauconitic greensand, in which there is more or less iron carbonate. This rock has been altered to a quartz-magnetite-amphibole slate, the amphibole being in the form of actinolite, grünerite, cummingtonite, and hornblende. This quartz-magnetite-amphibole slate, commonly known in the Lake Superior region as actinolite schist, has been profoundly changed by the gabbro, and the resulting rock is a coarse-grained aggregate of quartz, magnetite, olivine (which is mostly fayalite), hypersthene, augite, hornblende, and, occasionally, grünerite and cummingtonite."

The assumption of an intermediate state of metamorphism in the form of actinolite schist alluded to in the foregoing quotation has, until at present, obscured the problem of contact metamorphism by the gabbro, because these amphibolitic rocks were supposed to occur independently of the gabbro and of any igneous intrusion. Indeed, the rocks formerly regarded as "amphibolitic cherts" occur at a great distance from the gabbro. Thus Winchell supposes that grünerite makes its appearance in the iron-bearing rocks "under very slight provocation," but it attains "its complete display in the area that is most affected by the gabbro."[4] We now know definitely that no amphibolitic rocks exist in the western iron formation. The occurrence of amphiboles in the eastern area can be

[1] A. H. Elftman, "Preliminary Report of Field Work during 1893 in Northeastern Minnesota, "*Minnesota Geol. Survey, Annual Report 22* (1894), p. 168.

[2] "Field Observations of N. H. Winchell in 1897," *Minnesota Geol. Survey, Annual Report 21*, p. 86.

[3] *Bull. Geol. Society of America*, Vol. XI (1900), pp. 506, 507.

[4] *Geology of Minnesota*, Vol. IV, p. 396.

accounted for by the proximity of the gabbro. Moreover, the intrusion of the gabbro seems to be the only reasonable explanation for their occurrence. Evidently there were no particular dynamical disturbances which could account for the presence of the amphiboles in the east rather than in the west, nor is there any reason to assume the action of deep-seated processes in the east. The formation of a rock so highly metamorphosed as the grünerite rock from northeast of Mesaba, for example, or the quartz-magnetite-amphibole rocks at Babbitt, would require a considerable temperature. This would postulate a depression of the area to a depth of 8–10 miles; yet the neighboring ferruginous cherts, with greenalite still in a colloidal state, can never have been exposed to any great amount of temperature. In other words, we should have to suppose a fault between eastern and western deposits with a displacement of many miles, while in fact the formation passes continuously, without break, from the west to the east.[1]

Thus igneous intrusion alone is left to produce the metamorphism. The enormous adjacent batholith of gabbro which here cuts the iron formation at an acute angle is competent to produce metamorphism to such an extent. One objection, however, must be considered. Highly metamorphic rocks occur at a greater distance from the present surface boundaries of the gabbro than one would expect. The grünerite-magnetite rocks northeast of the Mesaba station, previously referred to, may be mentioned as an example of a highly metamorphosed taconite at a distance of almost 2 miles from the next outcrop of gabbro. Its metamorphism is the more surprising because Virginia shales, here between the iron formation and the gabbro, are not metamorphosed for a stretch of one mile. Only the last 900 feet of the shales, before the exposure of gabbro is reached, are changed to hard, massive hornfels with beautiful cordierite trillings. These conditions are well observable along the railroad tracks

[1] F. F. Grout and George A. Thiel described, in the *American Mineralogist*, Vol. IX (1924), pp. 228–31, a mineral intermediate between chlorites and biotites—stilpnomelane—occurring in veins in the Genoa pit on the Mesabi range and elsewhere. "Its association in veins with apatite and specularite indicates that it forms at high temperatures and at a considerable depth." The writer's opinion is that thermal solutions, ascending locally in the iron formation, could well account for the high temperature minerals of the veins, without the assumption of a depression to a considerable depth, which would be in disagreement with the non-metamorphic state of the surrounding rocks.

from Mesaba toward Allen Junction. Possibly an offshoot of the gabbroid magma moved northward along the layers of the iron formation. On account of the southward dip of these layers, such a sill might be near the present surface at Mesaba and close enough to the rocks metamorphosed to grünerite and magnetite, while the shales south of Mesaba, farther away from the sill, escaped its metamorphosing influence. A small diabase sill outcropping a little southwest of the grünerite rock[1] may be an apophysis of the larger sill. Grout and Broderick mention other sills and dikes intruded into the iron formation (p. 8). It is not known whether or not they belong to the same intrusion with the gabbro. In any case, they reveal igneous activity after the deposition of the Biwabik formation and at some distance from the outcrop of the main gabbro mass. The dependence of the metamorphism upon the intrusive masses of either the gabbro or the dikes and sills will be the aim of more detailed field work.[2]

Concluding this report on grünerite rocks of Michigan and Minnesota, the writer wishes to add that in the Ironwood formation of northern Wisconsin grünerite also occurs, as it seems, abundantly. Assistant State Geologist N. H. Aldrich had the kindness to send a core of a drill hole of the western Penokee-Gogebic range, Sec. 17, T. 44, N., R. 3 W. It consists predominantly of typical grünerite. Through the courtesy of Mr. Aldrich the writer was also enabled to examine thin sections of those rocks from Penokee gap, and west of it, which were described as "actinolite schists" in *U.S. Geol. Survey Monograph 19*. Grünerite is doubtless an important constituent of these rocks. Details must be worked out by further studies in field and laboratory.

On the other hand, no grünerite was found in the metamorphosed iron formation of the Vermilion district, Minnesota. The writer found inclusions of the Sudan formation in granite at the White Iron Beach, near Ely. It contains, in addition to magnetite, a strongly pleochroic amphibole whose maximum index is 1.658 and whose birefringence is less than 0.028.

[1] F. F. Grout and F. M. Broderick, "The Magnetite Deposits of the Eastern Mesabi Range," *Minnesota Geol. Survey, Bull. 17* (1919), p. 48 and map.

[2] Recent field work in the Mesabi Range has convinced the writer that grünerite is an important constituent of the metamorphic iron formation at many localities east of Mesaba. It occurs also in the vicinity of Babbitt in typical development, associated with blue-green amphibole.

THE OLENTANGY SHALE IN SOUTHERN OHIO

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ABSTRACT

This paper contains an account of the distribution and characteristics of the blue shale at the base of the Devonian system from Greenfield, Highland County, Ohio, to the Ohio River. Evidence is presented to show that this blue shale belongs to the same formation as the Olentangy shale of central Ohio, that it is local in its occurrence in southern Ohio, and that it rests disconformably on the underlying limestones and lies conformably beneath the Ohio shale, into which it grades in some localities. The field evidence supports the interpretation of Grabau that the Olentangy shale is a basal phase of the Ohio shale and that it is Upper Devonian in age.

INTRODUCTION

Above the Delaware limestone in central Ohio is a formation of soft, blue shale with a few thin limestone layers, which was named the Olentangy shale by N. H. Winchell[1] in 1874 from exposures along the Olentangy River near Delaware, Delaware County. In recent years this shale has been grouped with the underlying Delaware limestone to form the Erian series of the Devonian system of Ohio.

North of Delaware this shale outcrops as a narrow belt extending through central Delaware and Crawford, southeastern Seneca, and western Huron counties. Shale considered by Stauffer to belong to the same formation as the Olentangy shale of Delaware County outcrops in the region of Sandusky, Erie County, Ohio, appears in the Ausable River Valley in Lambton County, Ontario,[2] and has been penetrated by the drill near Sarnia and Corunna, in the western part of the same county.[3]

South of Delaware many exposures of this shale may be observed along the Olentangy River and its tributaries. From Colum-

[1] N. H. Winchell, *Geol. Survey Ohio*, Vol. II (1874), p. 284.

[2] C. R. Stauffer, *Geol. Survey Canada, Mem. 34* (1915), pp. 163–73.

[3] *Idem.*, pp. 192–94.

bus southward, exposures have been reported along Deer Creek, Pickaway County, and near Bainbridge in Ross County.[1]

In northern Kentucky, near Fox Springs, Fleming County, and Olympia Springs, Bath County, the blue shale reported by Foerste and Morse at the base of the Ohio shale suggests the southern continuation of the Olentangy formation in Ohio.[2]

In view of the widespread distribution of the Olentangy shale from central Ohio north to Ontario, Canada, it seems advisable to record any data relative to the presence of shale at this horizon in southern Ohio. Further interest is attached to this subject by the publication of a paper by Dr. C. R. Stauffer[3] on the relation of the Olentangy shale and associated Devonian deposits in northern Ohio, in which he considers that the Huron or lower part of the Ohio shale rests unconformably on the Prout limestone in northern Ohio, on the Olentangy shale in central Ohio, and locally on the Silurian limestone in southern Ohio. In recent years the writer has crossed the belt of Devonian outcrops at many places from Pickaway County south to the Ohio River and has studied the character, thickness, and stratigraphic relations of the blue shale at the base of the Devonian system. The data collected in the field and the conclusions drawn from these data furnish the basis of discussion in the pages that follow. The writer wishes to acknowledge his obligations to Dr. J. A. Bownocker and Dr. J. Ernest Carman for suggestions and advice in the preparation of this paper and for the reading of the manuscript, and to the Geological Survey of Ohio for financial aid in carrying on the field work.

THE OLENTANGY SHALE IN CENTRAL OHIO

At the type locality near Delaware, Ohio, the Olentangy shale has a thickness of 30 feet. The lower part of the formation consists of blue shale with concretionary masses of blue limestone, while the upper part is dominantly blue shale interstratified with thin layers of black shale, similar lithologically to the overlying Ohio

[1] C. R. Stauffer, *Geol. Survey Ohio, Bull. 10*, 4th series (1909), p. 38.

[2] A. F. Foerste and W. C. Morse, *Kentucky Geol. Survey Bull. 16* (1912), pp. 27, 37.

[3] C. R. Stauffer, "Relation of the Olentangy Shale and the Associated Devonian Deposits in Northern Ohio," *Jour. Geol.*, Vol. XXIV (1916), pp. 476–87.

shale. A section of these shales measured by Stauffer at Winchell's type locality is as follows:[1]

	Feet	Inches
22. Soil and drift	3	0
Ohio shale		
21. Badly weathered and much altered black shale	8	0
20. Black shale with some large more or less spherical concretions and some thin arenaceous layers at the contact below.	22	0
Olentangy shale		
19. Soft, blue, argillaceous shale	2	4
18. Horizon of discontinuous layer of flat blue limestone concretions	..	..
17. Soft, argillaceous, blue shale with a few thin layers of brown to black shale	5	4
16. Soft, argillaceous, blue limestone	0	4
15. Soft, blue shale	1	4
14. Brown to black shale with an occasional blue trail in it	0	4
13. Argillaceous, soft, blue shale	1	0
12. Layer of brown to black shale with blue trails	0	1
11. Argillaceous, soft, blue shale	2	6
10. Layer of brown shale with markings of blue	0	1
9. Soft, blue shale with a half-dozen or more thin layers of argillaceous, blue limestone, an occasional flat limestone concretion near the base. Two feet 7 inches above the base of this zone there is a remarkable bed of Crinoid fragments about midway along the cliff. It forms a lens of limestone with a maximum thickness of 5 inches and extends along the cliff for a distance of 13½ feet	4	10
8. A persistent layer of flat limestone concretions	0	8
7. Soft, blue shale with an occasional flat disklike concretion.	1	6
6. Persistent layer of disklike concretions	0	4
5. Soft, argillaceous, blue shale with several discontinuous layers of disklike or flat concretions	3	0
4. Rather definite layers of flat irregular limestone concretions	0	5
3. Soft, argillaceous, blue shale with a few rather irregular blue limestone concretions	3	4
2. Argillaceous, blue limestone breaking with a very irregular and conchoidal fracture	0	4
1. Soft, argillaceous, blue shales tending to be massive, to level of Olentangy River	0	4

The Delaware limestone outcrops, according to Stauffer, about 3 feet below the base of this section.

[1] C. R. Stauffer, *Geol. Survey Ohio, Bull. 10*, 4th series (1909), pp. 88–89.

THE OLENTANGY SHALE IN NORTHERN OHIO AND IN ONTARIO, CANADA

From Delaware north, good exposures of the blue shale above the Delaware limestone are rare until the region of Lake Erie is reached. About 2 miles southeast of Prout Station, Erie County, shale considered by Stauffer to represent the Olentangy formation was formerly well exposed along Plum Run. Stauffer reports the following section taken at this place:[1]

	Feet	Inches
Huron shale		
12. Shale, bituminous, black	4	0
Widder beds		
11. Prout or Encrinal limestone. A very hard, siliceous, blue limestone containing a little chert and much pyrite. Silicified corals and crinoid stems are abundant, the latter especially in the middle layers	8	10
Olentangy shale		
10. Covered interval	6	0
9. Limestone, soft, blue, very fossiliferous	0	6
8. Shale, argillaceous, soft, blue	3	6
7. Limestone, quite hard, blue	0	6
6. Shale, soft, blue	5	0
5. Limestone, blue, lower part shaly, very fossiliferous	0	6
4. Shale, argillaceous, soft, blue. This shale contains numerous small pyrite concretions, some of which are beautifully twinned crystals. The fossils are probably rare in most of it, and appear to be in streaks or layers. Mostly covered	10±	0
3. Shale, blue, with pyritized fossils	0	6±
2. Shale, blue, fossils rather abundant	3	0
1. Shale, soft, blue, with some flat calcareous concretions. Fossils rare	5	0

In the Ausable River Valley of Ontario, Canada, blue shale is found below the Widder beds similar lithologically to the blue shale below the Prout limestone in northern Ohio. Stauffer considers that this shale belongs to the same formation as the Olentangy shale of central Ohio. He records the following section from Arkona, Lambton County.[2]

[1] C. R. Stauffer, *Jour. Geol.*, Vol. XXIV (1916), pp. 476–77.

[2] C. R. Stauffer, *Geol. Surv. Canada, Mem. 34* (1915), p. 163.

	Feet	Inches
Widder beds		
10. Massive, argillaceous, blue limestone alternating with blue shale and all quite fossiliferous. These beds form the top of the fall by the old mill	10	8
9. Rather soft, blue shale with calcareous nodules or concretions. *Spirifer mucronatus* is a conspicuous and abundant fossil in the lower layers	8	4
8. Argillaceous, blue limestone with some fossils	1	6
7. Soft, blue shale with some layers that are a little more massive than the others. Fossils rather abundant and in several of the layers they are crowded together	17	4
6. Rather massive shale and several layers of shaly blue limestone in the lower part	7	0
5. Coral zone. A decomposed gray-to-blue shale or impure shaly limestone filled with corals	3	6
4. Encrinal limestone. A hard, pyritiferous, bluish-gray limestone which is a mass of crinoidal segments, coral fragments, and other fossils. It includes some brown shale near the base	2	4
Olentangy shale		
3. A soft, gritless, blue shale in which fossils are rather rare	19	0
2. A soft, blue shale with a few thin lenses of crinoidal limestone and an occasional flat, calcareous concretion. Fossils are fairly abundant in these beds and especially in the lenses of limestone	10	0
1. Covered interval to the level of the Ausable River	10	0

OLENTANGY SHALE IN SOUTHERN OHIO

The field of study in southern Ohio includes the belt of Devonian shale outcrops from southern Pickaway County to the Ohio River. In this area the contact of the Devonian shale and Silurian limestone was studied in twenty-two localities which are shown on the accompanying map (Fig. 1). At eighteen of these localities blue shale, similar lithologically to the Olentangy shale of central Ohio, occurs in contact with the Silurian limestone and forms the basal phase of the Devonian system, while at four localities blue shale is entirely wanting and the black Ohio shale rests on the limestone. The following sections have been selected to illustrate the character and mode of occurrence of this blue Devonian shale in southern Ohio.

BLACK HOLLOW SCHOOL

Black Hollow School is located in the south-central part of Franklin Township, Adams County, $4\frac{1}{4}$ miles northeast of Peebles.

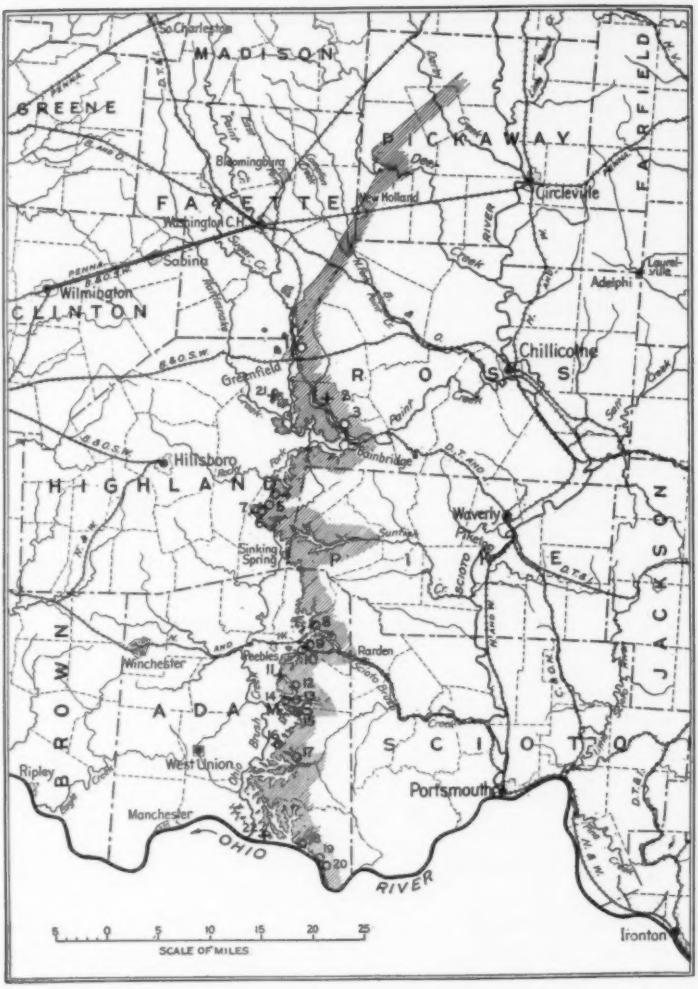

FIG. 1.—Map of southern Ohio showing location of outcrops of the Olentangy shale: O, localities where the Olentangy shale is present; +, localities where the Olentangy shale is wanting.

The following section records the character of the outcrops along the road by the schoolhouse (Locality 8):

	Feet	Inches
Ohio shale		
11. Black, fissile, carbonaceous shale	10	0
Olentangy shale		
10. Bluish-gray shale	6	2
9. Black, carbonaceous shale	0	6
8. Blue shale	1	4
7. Black, carbonaceous shale	2	0
6. Soft, blue shale	33	10
5. Black shale, weathering to a chocolate brown	5	2
4. Blue shale, with an occasional layer of black shale	7	6
3. Soft, bluish-gray shale	3	0
2. Nodular iron ore	0	2
Monroe dolomite		
1. Dolomite	2	0

MOUNT ZION SCHOOL

Seven-eighths mile west of Mount Zion School, in the western part of Jefferson Township, Adams County, blue shale is well exposed in contact with the Silurian limestone along a road near the headwaters of a small tributary to the Ohio Brush Creek. A section of the outcrops at this locality follows (Locality 16):

	Feet	Inches
23. Black, carbonaceous shale	6	0
22. Gray shale	0	5
21. Black, carbonaceous shale	1	1
20. Bluish-gray shale	0	6
19. Black, carbonaceous shale	0	5
18. Bluish-gray shale, a little arenaceous	0	10
17. Black, carbonaceous shale	0	2
16. Bluish shales	0	4
15. Black, carbonaceous shale	2	0
14. Blue shale	0	8
13. Black, carbonaceous shale	1	4
12. Bluish-green shale	0	10
11. Black, pyritiferous shale	0	1
10. Bluish-green shale	1	0
9. Black shale, weathering to a chocolate color	1	2
8. Blue shale	1	6
7. Black, ferruginous shale	0	1
6. Blue shale	1	1

	Feet	Inches
5. Black, ferruginous shale	0	1
4. Bluish-green shale	2	4
3. Blue, pyritiferous shale	2	9
2. Bluish-green shale, weathering to a red clay	9	5
1. Niagara dolomite, badly weathered	3	0

THE OHIO RIVER VALLEY

The Silurian-Devonian contact in the Ohio River Valley follows a very irregular line from the Ohio Brush Creek eastward to a point one mile southwest of Sandy Springs. Along the streams tributary to the Ohio River several good exposures of the basal shales of the Devonian may be seen. About five-eighths mile northwest of Long Lick Run a deep ravine has been cut into the limestone, and near its head the base of the Devonian shale is well exposed (Locality 18). A section of the shale follows:

	Feet	Inches
Ohio shale		
15. Black, carbonaceous shale	10	0
Olentangy shale		
14. Bluish-gray shale	1	6
13. Black, carbonaceous shale	0	11
12. Blue shale	0	10
11. Black, carbonaceous shale	1	2
10. Bluish-gray shale	2	3
9. Black, carbonaceous shale	0	2
8. Blue shale	1	1
7. Black, carbonaceous shale	0	2
6. Blue shale	0	10
5. Black, arenaceous, ferruginous shale	1	0
4. Bluish-gray shale	3	0
3. Black, carbonaceous shale	0	3
2. Bluish-gray shales with many nodules of iron pyrite	8	10
Monroe dolomite		
1. Dolomite, badly weathered	5	0

The preceding sections illustrate the alternation of black and blue shale so characteristic of the basal unit of the Devonian shale of southern Ohio. In some localities the beds of black shale are thin, and their aggregate thickness is only a small fraction of the total thickness of the interstratified blue and black shale. At such places the contact between the Olentangy and Ohio shale formations is drawn at the top of the highest blue shale bed. Elsewhere, these

black shale beds become more prominent, and may equal or exceed the interstratified blue shale in thickness. In such cases no arbitrary line is drawn between these two formations.

SALIENT FEATURES OF THE OLENTANGY SHALE OF OHIO

In the preceding pages the chief purpose of the writer has been to emphasize the character, thickness, and location of outcrops of the Olentangy shale. A comparative study of the stratigraphic relations and physical characteristics of this formation reveals the following facts:

1. In central and northern Ohio and in Ontario, Canada, the Olentangy shale rests on the Delaware limestone; but in southern Ohio it overlaps successively on the Columbus limestone, the Monroe dolomite, and the Niagara dolomite.

2. In the province of Ontario, Canada, and the Sandusky region of Ohio, the Olentangy shale of Stauffer is overlaid by the Encrinal or Prout limestone, the basal member of the Widder beds. At Delaware and southward in Ohio, this limestone is wanting and the Ohio shale rests on the Olentangy formation.

3. Throughout the northern part of the area under consideration a characteristic feature of the Olentangy formation is the presence of thin layers of compact blue limestone or concretionary masses of blue limestone arranged in definite zones or distributed irregularly throughout the shale. Limestone of this nature occurs as far south as Bainbridge, but is wanting in localities farther to the south. The limestone, together with the associated shale, is fossiliferous in the Delaware and Sandusky regions, although no fossils have been found in localities south of Columbus.

4. Along the Olentangy River from Columbus northward through Franklin and Delaware counties, and even across the divide as far as Sandusky, Erie County, exposures at this horizon show that the Olentangy shale is normally present in thicknesses ranging from 23 feet to 40 feet. In contrast to this regularity, the Olentangy formation from Deer Creek, Pickaway County, south to the Ohio River is local in its development, being completely absent at many localities.

5. On lithological grounds the plane of separation between the

Olentangy shale and the overlying formation is not distinct in southern Ohio. The layers of black shale which occur interstratified with the blue shale, and which characterize the Olentangy shale in central Ohio, increase in number toward the south. In some localities the Olentangy shale passes by decrease in the amount of blue shale and increase in black shale into the overlying formation in such a manner that it is quite arbitrary where the contact is drawn.

THE SHALE-LIMESTONE CONTACT IN SOUTHERN OHIO

A striking feature of the Olentangy shale of southern Ohio is the overlapping relations on older formations. As far as field study shows, this formation rests conformably on the Delaware limestone in central and northern Ohio, but in southern Ohio it rests, in order, on Columbus limestone, Monroe dolomite, and Niagara dolomite. A number of exposures showing the contact of the Olentangy shale with the older formations have been observed along the line of outcrop from Greenfield south to the Ohio River. Although the overlapping relations of the shale indicate a disconformity at the base of the formation, these relations are not always evident from exposures of the contact. The limestone layers tend, in general, to parallel the shale contact within the limits of a single exposure. The upper surface of the limestone often shows gentle undulations, but no deep pitting or solution channels such as would be expected from prolonged erosion. Locally, the upper layers of the limestone are very ferruginous, or are overlaid by a thin bed of ferruginous material, approaching iron ore in composition, which suggests an old erosion surface. Ore material of a similar nature has been reported by Kindle[1] to occur at the limestone–black shale contact in Boyle, Lincoln, Montgomery, and Casey counties, Kentucky, where there is good field evidence of a disconformity.

The Onondaga limestone (Columbus) disappears from the section in Pickaway County, Ohio, and reappears in Fleming County, Kentucky,[2] while the blue shale representing the Olentangy formation has been recognized in Kentucky at various localities as far

[1] E. M. Kindle, "Unconformity at the Base of the Chattanooga Shale in Kentucky," *Amer. Jour. Science*, 4th series, Vol. XXXIII (1912), pp. 122–23.

[2] A. F. Foerste, *Kentucky Geol. Survey Bull. 7* (1916), p. 130.

south as Waco,[1] Madison County, but is wanting farther to the southwest.

To the writer's knowledge, no well-defined erosion surface has been recognized at the base of the Olentangy shale in Kentucky. Kindle,[2] however, describes a disconformity at the base of the Ohio shale at Crab Orchard, Lincoln County, and Riley's Station, Marion County, where these black shales overlap on the Devonian limestone.

The absence of the Middle Devonian limestone in Pickaway, Highland, Ross, and Adams counties, Ohio, and Lewis County, Kentucky, can be interpreted in one of two ways. Either the territory was an old land area during Onondaga time, and therefore subject to erosion rather than deposition, or there was an emergence of the land in post-Onondaga time followed by an erosion period of sufficient length to remove all traces of Devonian limestones and to cut deeply into the Silurian rocks before the period of submergence took place which inaugurated the deposition of the Olentangy and Ohio shales. In either case the stratigraphic relations of the Olentangy shale to older rocks would be one of disconformity. The surface of the contact, so far as single exposures are concerned, is flat and featureless, as is further indicated by the lack of anything like a conglomeratic phase at the base of the Olentangy shale. That the land surface upon which the sea gradually encroached at the beginning of the period of shale deposition was not without some relief can scarcely be imagined, but a comparison of the elevations of the shale-limestone contact at different localities furnishes no data of a conclusive nature. At many places, however, from Greenfield south to the Ohio River, black shale is found to rest directly on the limestone with no evidence of the intervening blue Olentangy shale. Therefore, locally at least, either the limestone projected above the shallow seas in which the blue sediments were being deposited, or the conditions necessary for the formation of black shale prevailed from the beginning of the period of shale deposition. The fine texture of the blue shale and the even bedding, most marked where

[1] A. F. Foerste, *Kentucky Geol. Survey Bull. 7* (1916), pp. 104–5.

[2] E. M. Kindle, "Unconformity at the Base of the Chattanooga Shale in Kentucky," *Amer. Jour. Science*, 4th series, Vol. XXXIII (1912), pp. 122–27.

blue and black shales are interstratified, suggest very quiet conditions of deposition.

THE OLENTANGY-OHIO SHALE CONTACT IN SOUTHERN OHIO

In Lambton County, Ontario, the Olentangy shale is overlaid by the Widder beds, above which, in ascending order, come the Petrola shale, Ipperwash limestone, and Devonian black shale. Stauffer reports that the interval from the base of the Huron shale to the Encrinal limestone at Kettle Point, Ontario, where the rock succession is the same as in Lambton County, is 160 feet.[1] This thickness of 160 feet is overlapped southward in crossing Lake Erie, for in northern Ohio the Devonian black shale rests on the Prout limestone. When traced south from the Sandusky region, the Devonian black shale is found to overlap on the Olentangy formation in Delaware and Franklin counties in central Ohio, and locally on the Monroe dolomite in southern Ohio.[2] Stauffer considers the black shale to be disconformable on the underlying beds,[3] although the disconformity is not apparent at most rock exposures.

Stauffer's interpretation is in striking contrast to the opinion of Grabau, who has likewise made a field study of the Olentangy shale in Delaware County and of the Prout limestone[4] (Widder) and associated beds in northern Ohio. The presence of thin bands of black shale interstratified with the blue Olentangy shale leads Grabau to the conclusion that deposition was continuous from the Olentangy to the Ohio shale, and therefore no disconformity marks the contact of these two formations.

As stated in the preceding pages, the upper part of the blue Olentangy shale in southern Ohio is interstratified with many layers of black shale. Both the blue and the black shale zones of the Olentangy formation are parallel to the upper formation contact, which shows no characteristics of a plane of disconformity. Fur-

[1] C. R. Stauffer, "Relation of the Olentangy Shale and the Associated Devonian Deposits in Northern Ohio," *Jour. Geol.*, Vol. XXIV (1916), p. 485.

[2] *Idem.*, p. 486.

[3] *Idem.*, p. 487.

[4] A. W. Grabau, "Age and Stratigraphic Relations of the Olentangy Shale of Central Ohio, with Remarks on the Prout Limestone and So-Called Olentangy Shales of Northern Ohio," *Jour. Geol.*, Vol. XXV (1917), pp. 337–43.

thermore, the frequent recurrence of black shale in the Olentangy so similar in physical characteristics to the Ohio black shale formation above is difficult to harmonize with the idea of a distinct stratigraphic break between these formations, representing the time necessary for the deposition of the Widder, Petrola, and Ipperwash formations of Ontario, Canada. It is much more plausible to consider that these black shale beds of the Olentangy formation represent periods of time when the conditions for black shale deposition were temporarily met; that these conditions recurred from time to time, and finally became dominant in this inland sea during the deposition of the Ohio shale. It is therefore the conclusion of the writer, supported by all the known field evidence, that the Ohio shale of southern Ohio rests conformably on the Olentangy shale.

The two interpretations of the stratigraphic relations of the Olentangy and Ohio shale lead to the following possibilities involving the unity of the blue shale formation from the Ohio River north to Ontario, Canada, and its geologic age:

1. The Olentangy shale of central and northern Ohio is not the same formation as the blue shale of southern Ohio. According to Stauffer's interpretation, the Upper Devonian black shale lies unconformably upon the underlying beds in central and northern Ohio. The base of this formation descends from the Ipperwash limestone of Kettle Point, Ontario, to the Prout limestone in the Sandusky region of northern Ohio, to the Olentangy shale in central Ohio, and to the Silurian limestone in southern Ohio. Field studies in southern Ohio lead to the conclusion that a blue shale, which by all appearances is the same as the Olentangy shale of central Ohio, lies conformably below the Ohio shale and locally grades into it. The blue shale in the latter region would therefore be Upper Devonian in age, while the Olentangy shale in central and northern Ohio is usually considered to belong to the Erian series of Middle Devonian.

2. The blue shale of southern Ohio belongs to the same formation as the Olentangy shale of central Ohio, but this shale in these two regions is not the same formation as the blue shale underlying the Widder beds in northern Ohio and Ontario, Canada. The Ohio shale rests conformably on the Olentangy shale in southern Ohio

and, according to Grabau, conformable relations exist between these formations in central Ohio. On this interpretation, the Olentangy shale–Delaware limestone contact in central Ohio represents a long period of time during which the Widder, Petrola, and Ipperwash formations of Ontario, Canada, were being deposited. The Olentangy shale is thus conceived to rest on the Silurian limestone in southern Ohio, and successively on the Columbus and Delaware limestones in central Ohio. North of Delaware County the Olentangy shale by this interpretation disappears from the section, and the overlying Ohio shale rests disconformably on the Prout limestone in northern Ohio and on the higher Devonian limestones in Ontario, Canada. The Olentangy shale would thus be a phase of the Ohio shale, and Upper Devonian in age.

3. The blue shale of southern Ohio belongs to the same formation as the Olentangy shale of central and northern Ohio and Ontario, Canada. The Ohio shale rests conformably on the blue shale in southern Ohio and, by this interpretation, it might rest conformably on the Olentangy in central Ohio, on the Widder in northern Ohio, and in order on the Petrola and Ipperwash of Ontario, Canada. The Widder, Petrola, and Ipperwash formations are considered to wedge in between the Olentangy shale and Ohio shale on Ontario, Canada, but to thin and disappear to the south. By this interpretation the succession from the base of the Olentangy to the top of the Ohio shale is a conformable series, but notable differences occur in this series from Canada to southern Ohio. This difference is considered to be due to lateral gradation in the sediments. Clear water conditions free from land detritus must have prevailed at times during the deposition of the Middle Devonian sediments in Ontario, Canada, while at the same time black shale was being deposited in central and southern Ohio. Therefore, the lower part of the Ohio black shale found in the latter regions must be Middle Devonian in age.

THE OLENTANGY-OHIO SHALE CONTACT IN CENTRAL OHIO

The writer has studied the Olentangy-Ohio shale contact at several well-known exposures in Delaware and Franklin counties, and at no place has he found any evidence of disconformity between

these formations. On the contrary, it seems to the writer that there was continuous deposition, but with a more abrupt transition from blue to black shale than is shown by the exposures in southern Ohio. The upper part of the blue Olentangy shale is interstratified with many thin layers of black and brown shale. At the exposure along the tributary to the Olentangy River, which heads near Lewis Center in southern Delaware County, at High Banks near the Franklin-Delaware county line, and along Slate Run, a tributary to the Scioto River in Franklin County, black shale layers are present in the upper few inches of the Olentangy formation, which show no appreciable variation in thickness or change in their position relative to the contact within the limits of the exposure. These features are not in harmony with the idea of a distinct stratigraphic break between the blue and black shale.

CONCLUSIONS

On the basis of the evidence discussed in this paper the writer comes to the following conclusions:

1. The blue shale of southern Ohio belongs to the same formation as the Olentangy shale of central Ohio. This shale is local in its occurrence in southern Ohio, lies conformably below the Ohio shale, and, by increase in the amount of interstratified black shale, grades into the Ohio shale at places in such a manner that no line of separation on lithological grounds can be drawn beween the two formations. The Olentangy shale is a basal phase of the Ohio shale, and therefore Upper Devonian in age.

2. The Olentangy-Ohio shale rests disconformably on the Silurian limestones in southern Ohio, successively on the Columbus and Delaware limestones in central Ohio, and, following the interpretation of Grabau, it is believed to rest disconformably on the Prout limestone in northern Ohio and on higher Middle Devonian limestones in Ontario, Canada.

3. Since the Olentangy shale in central and southern Ohio is Upper Devonian in age, it is not the same formation as the blue shale below the Widder beds (Middle Devonian) in northern Ohio and in Ontario, Canada.

THE PRIMARY STRUCTURE OF THE KEKEQUABIC GRANITE

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ABSTRACT

Directive features in the Kekequabic granite of northeastern Minnesota were mapped for the purpose of determining the relation of the intrusion to the tectonic forces responsible for the intense regional folding of sediments intruded by the granite. The results indicate a lateral movement of the magma from the southwest, paralleling the trend of the regional folding, during the existence of pressures from the northwest and southeast. The structure of the sediments shows that these pressures were responsible for the regional folding, and the granite is assumed to have followed shortly after such folding and to be directly related to the same period of diastrophism.

INTRODUCTION

The Kekequabic granite outcrops about the southern shore, and constitutes several small islands in the western half of Kekequabic Lake, just south of the Ontario boundary in Lake County, northeastern Minnesota. The exposure is roughly elliptical in outline, occupies about five square miles, and is elongated parallel with the lake and the trend of the regional folding, slightly north of east (Fig. 1). The granite intrudes steeply dipping and highly metamorphosed sediments of Lower or Middle Huronian age. If younger formations were deposited in the area, they have long since been eroded. In studying the geology of the area during parts of the summers of 1925 and 1926, the question arose as to the age of the intrusion and its relation to the tectonic forces responsible for the intense folding of the adjacent sediments. At the suggestion of Professor U. S. Grant, an attempt was made to determine the primary structure of the granite by application of the new methods developed by Professor Hans Cloos[1] and his associates in working out the structure of the granite massives in the extensive quarries of Strehlen, Silesia, and more re-

[1] *Tektonik und Magna Untersuchungen zur Geologie der Tiefen* (herausgegeben von H. Cloos; Berlin, 1922); *Das Batholithenproblem* (Berlin: Gebr. Borntraeger, 1923); *Einführung in die tektonische Behandlung magmatischer Erscheinungen* (Granittektonik) (Berlin: Gebr., 1925).

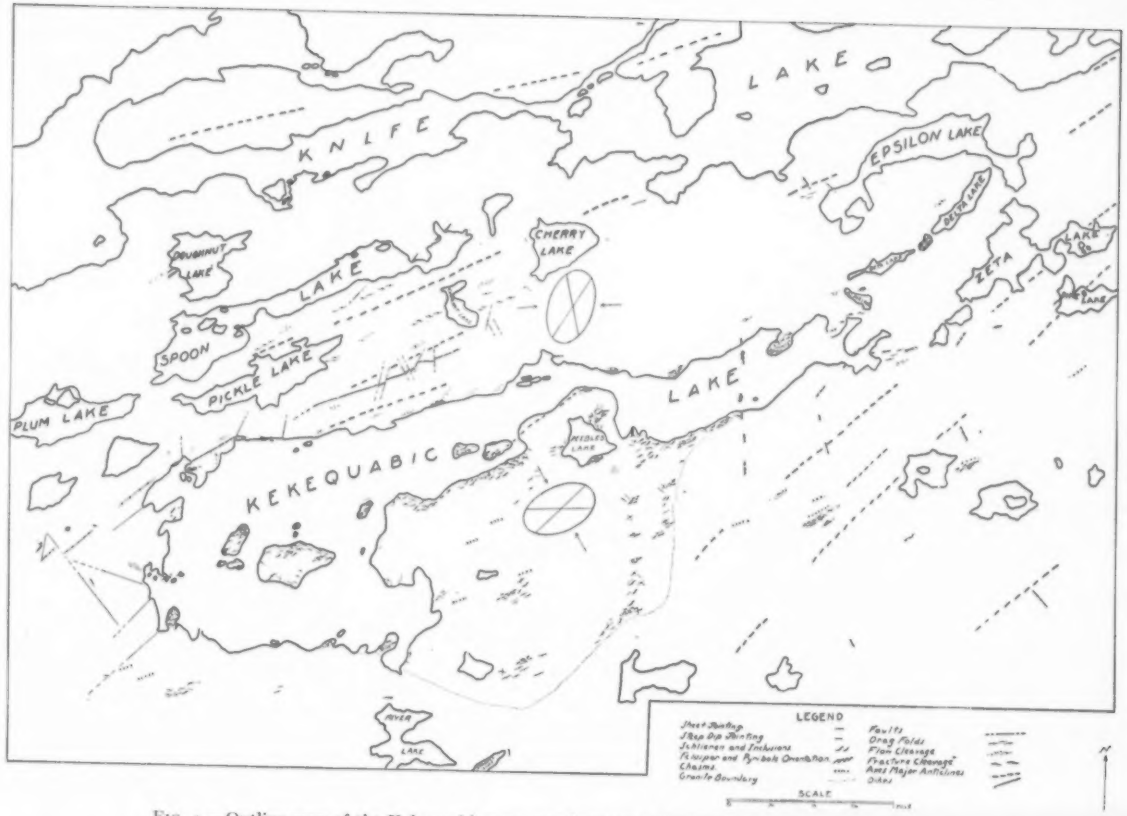

FIG. 1.—Outline map of the Kekequabic area, northeastern Minnesota, showing structural features.

cently applied by Robert Balk,[1] a pupil of Professor Cloos, to granites in Vermont.

These methods consist of plotting schlieren, flow lines, joints and dikes, and from concentric lines inferring directions of movement. A relation between the rising magna and the tectonic forces is believed to have been established, indicating that the materials while rising were affected by the forces, that their origin and present location were influenced by movements and zones of weakness of the country rock, and that granites do not all continue to considerable depths.

The writer desires to make grateful acknowledgment for the help of Professor U. S. Grant, of Northwestern University, under whose guidance the field work was carried out; and to Professors Albert Johannsen and R. T. Chamberlin, of the University of Chicago, for their helpful suggestions and criticism throughout the laboratory work and preparation of the report.

CHARACTER OF THE KEKEQUABIC GRANITE

Under the heading of "Kekequabic Granite" have been grouped a series of aschistic and diaschistic rocks which are thought to have emanated from the same general magna. In type areas, at least four facies show distinctive characteristic differences. These are (1) syenodiorite or shonkonite-like facies, (2) monzonite facies, (3) normal soda-augite granite, (4) granite porphyry or porphyritic facies. In many cases, however, these are gradational into one another. The monzonite appears to be a later and more or less intermediate facies between the syenodiorite and the normal massive granite. The porphyritic facies cuts the normal granite locally with sharp dikelike contacts, but many porphyritic areas occur in the massive granite with gradational boundaries across which no intrusive relationship is observable either in field outcrops or in thin sections from specimens across the gradation. The order of occurrence is in general that of the foregoing sequence, but there are many exceptions.

Normally the granite is a medium- to fine-grained rock of granitoid texture and varies in color from a deep pink to a dull pinkish gray. In all facies the feldspars form the most abundant constituents

[1] "Structure of Granite Massives," *Bull. Geol. Soc. of Amer.*, Vol. XXXVI (1925), pp. 679–96.

FIG. 1.—Outline map of the Kekequabic area, northeastern Minnesota, showing structural features.

and give color to the rock. In some exposures the feldspars and a dark-green pyribole are all that can be distinguished. Under the hand lens quartz can usually be recognized, but in many specimens it is not seen and the rock would classify in the field as a syenide.[1] An even-grained, compact facies of the granite is found in all parts of the mapped outcrops, and it is certainly predominant enough to characterize the intrusion, but locally many exceptions to the even-grained texture occur.

The modes of thirty specimens of the normal granite from all parts of the outcrop show the following average composition:

Primary	Percentage
Orthoclase	11
Micro-perthite	43
Oligoclase	25
Augite	7
Aegerite-augite	3
Diopside	1
Hornblende	2
Quartz	7
Accessory microcline, micro-pegmatite, apatite, titanite, zircon, magnetite, pyrite, and biotite	1
	100

Secondary hornblende, actinolite, biotite, white mica, kaolinite, chlorite, epidote, and iron ores are present in varying amounts.

DIRECTIVE FEATURES OF THE PRIMARY STRUCTURE

One of the most prominent features of the Kekequabic granite, both in its massive and in its border facies, is the striking parallelism of the feldspar crystals, an example of which is shown in Figure 2. The direction of the parallelism and the dip of the flat, tabular faces of the feldspar crystals were plotted wherever found, and the results of these observations are shown in Figure 1. The directions of orientation vary locally, as seen in exposures of only a few feet square, but in general the directions are surprisingly constant. They exhibit a prevailing trend east and west with the majority of variations slightly northeast. The dip of most of the flat faces of the feldspars

[1] Albert Johannsen, "A Revised Classification of Igneous Rocks," *Jour. Geol.*, Vol. XXXIV (1926), pp. 181–82.

is nearly vertical, but again there are slight variations to the north and south. Many measurements were taken on each exposure, and only rarely was a wide departure from the normal position observed.

In addition to the several hundred field measurements, many specimens were collected from all parts of the granite outcrop. The field orientations were marked upon the specimens before breaking them from the bed rock, and thin sections were then cut along speci-

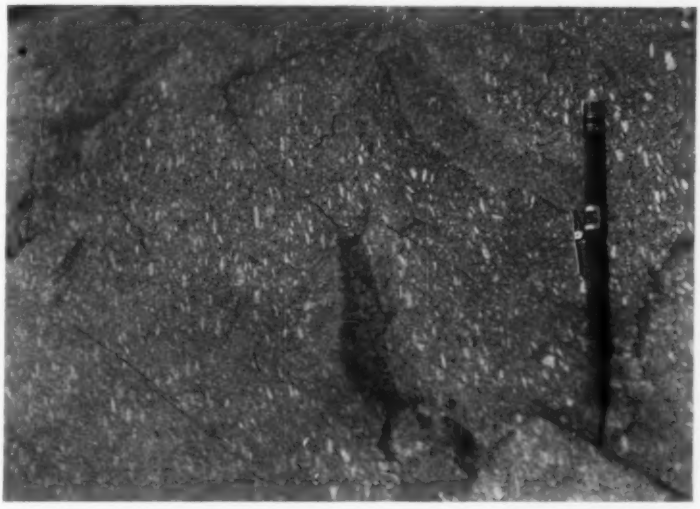

FIG. 2.—Porphyritic facies of the Kekequabic granite, showing well-developed parallel orientation of the feldspar crystals.

fied directions. This was done with the purpose of discovering, if present, any stretching or "streckung" structures, which forms a prominent feature of the Strehlen granites studied by Professor Cloos,[1] and from which the primary structure in the granite massive was largely inferred. There was abundant evidence of parallelism and flow structure in the orientation of the feldspar crystals in many parts of the Kekequabic granite which were not recognizable in the field exposures; the directions conform to the east-west directions of the larger crystals and are plotted on the map shown in Figure 1.

[1] *Op. cit.*, p. 681.

In regard to the apparent absence of stretching in many granites, Dr. Balk states: "So far as yet studied not many granites show the stretching as well as the Strehlen granite. Sometimes especially careful attention is necessary to recognize this structure in the field. It is so elusive that thin sections generally fail to show it even in well stretched rocks."[1]

The splitting of granite most easily along the "rift" and with difficulty at right angles to it is a well-known phenomenon. T. N. Dale[2] considers this to be to the original planes of weakness in the rock, which are the result of parallel boundaries between the minerals. Professor Cloos believes that this linear parallelism between the minerals is due to differential movement in the magma, as most of the inclusions in the granite massives that he has studied point with their longest axes nearly or quite parallel to the strike of the stretching, and the numerous schlieren or dark waves in the granite follow the same direction. Dark waves and streaks occur in many exposures of the Kekequabic granite. In every occurrence the schlieren streaks and inclusions are elongated with their long direction parallel to the long direction of the feldspar crystals. Movements in the granite magna are clearly indicated in this general east-west direction.

Dr. Balk states that within a given massive the strike of the stretching changes very little, and that convection currents are almost lacking,

> even next to contact lines the parallelism does not change its strike notably. It can be shown that such phenomena are impossible without the actual co-operation of the tectonic, non-magmatic forces, which make magmas yield to their stresses. Thus a north and south pressure would cause an east and west yielding and stretching as at Strehlen, Silesia; and east and west pressure would produce a north-south striking parallelism of the minerals, as at Bethel, Vermont. By measuring the strike of this stretching, therefore, we have likewise the direction of tectonic pressure during the time of intrusion.[3]

In the Kekequabic granite the stretching indicated by the schlieren, elongated inclusions, and the feldspar and pyribole crystals, all

[1] *Ibid.*

[2] "The Commercial Granites of New England," *U.S. Geol. Survey Bull. 738* (1923), pp. 19–20.

[3] *Op. cit.*, p. 683.

oriented parallel to the trend of the major folding in the area, suggests an apparent close connection between the magmatic intrusion and the tectonic forces responsible for the folding. That is, the pressure has been in the main slightly north-northwest–south-southeast, and the resulting parallelism produced in the granite was at right angles to this direction, if it is true, as Professor Cloos believes, that the parallelism is a direct result of pressures normal to the stretching.

The question naturally arises as to whether or not the feldspar orientation and the elongation of the schlieren may not have resulted from magma flowing along the direction of easiest escape regardless of lateral pressures. The feldspar crystals, however, are not only elongated east and west but they are on edge, with the broad, flat surfaces dipping approximately vertically. In case of a simple east-west movement, without pressure from north and south, this parallelism of the tabular faces would not be expected. In the schlieren waves and inclusions there is also a noticeable tendency toward a vertical elongation but with more pronounced stretching east and west.

The Kekequabic granite is highly jointed, in places badly shattered, and much time was spent in plotting the strike of the joints in all of the exposed outcrops. More than three hundred measurements were taken and plotted on the sketch map shown in Figure 1, with the exception of joints in the extremely shattered granite which may have been affected by concealed movements of large blocks. A few local variations occur, but in the main there is a striking tendency in the lines bisecting the acute angles of the intersecting joints to parallel the periphery of the granite outcrop. That is, the two principal directions of jointing are N. 50°–60° E., and N. 50°–60° W. This applies to the joints whose dips approach verticality and which are most persistent throughout the entire exposure. A third system of sheet jointing is prominently developed along the northwest boundary of the mass. These joints dip at low angles, paralleling the slope of the surface, away from the high central portion of the granite area. This inclined jointing appears to be of later origin than the vertical jointing, and is assumed to be due to adjustments of internal strain after relief of the overlying load by erosion.

In the thin sections cut according to definitely marked directions

in the field, the small fracturing of the crystals is predominantly in two directions which correspond to the major series of larger joints seen in the field. This microscopic fracturing is remarkably constant. Twenty to thirty measurements were made on each thin section, and in each slide the fractures varying widely from the two prevailing directions were never more than two or three.

The jointing in the German and Vermont granites appeared definitely related, and more or less at right angles, to the stretching structure. In Figure 3 a cross-section of the Kekequabic granite is diagrammed with the stretching direction indicated by the known feldspar orientation and the elongation of the schlieren and inclusions. The jointing cuts this direction at nearly right angles. The dotted boundaries of the granite below the surface are purely hypo-

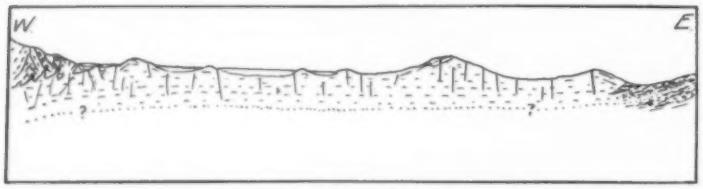

FIG. 3.—Diagrammatic cross-section through the Kekequabic granite, showing the relation of the stretching to the jointing.

thetical. They are drawn on the assumption that the shape of the granite is more that of a sheetlike mass than a deep-seated batholith.

At the western end of the granite exposure the steeply dipping sediments bend around the igneous intrusive to a north-south strike. For several hundred feet west of the granite, the slates are baked to hornfels and cordierite knotenschiefer in significant contrast to the narrow two- or three-inch contact zone in the sediments adjacent to the granite north and south of its elongate mass. West of the granite the sediments are also complexly faulted. A syncline overturned slightly to the west has been faulted into horst blocks which show a reversal of dip toward the granite.

The elongate shape of the granite outcrop, the faulting and tilting of the sediments at the west end of the lake, the greater extent of the contact metamorphism west of the granite, and the presence of a much larger mass of granite, with which the Kekequabic granite is identical petrographically, about the shores of Snowbank Lake

only ten miles to the southwest, i.e., in the direction from which the field evidence indicates the granite moved, are all suggestive of a lateral rather than a vertical intrusion. This assumption is further supported by the absence of dikes or bodies of granite in the sediments to the north and south of the elongate igneous outcrop and by the presence of several masses of granite a mile farther east of the eastern termination of the main granite outcrop. The Kekequabic granite is believed to be a satellite of the Snowbank Lake batholith, a term which F. F. Grout[1] has used in this connection to indicate small outlying plutonic masses.

It was originally believed that the granite would show convergence of the stretching toward the central portion because of the bending of the sedimentary beds around the west end of the granite mass where the dip to the east suggested movement of the magma outward over the dipping beds. It was only upon plotting the work of the two summers that the present interpretation was deduced. The discovery of the microscopic fracturing was a wholly unexpected corroboration of the jointing directions mapped in the field. The bending of the sediments around the western outcrop of the granite may have been the result of uplift due to the intrusion with exposure of the upturned beds by later erosion. If the granite was intruded from the west, as is assumed in the present hypothesis, it must have cut across the sediments and in so doing produced a drag reversing the original dip. The faulted horst block and the extreme shattering of the granite and slates indicate that this area was a zone of intensive dynamic metamorphism. Intrusion from this direction would also explain the knotenschiefer developed in the slates at the west end of the lake.

RELATION OF THE GRANITE TO THE REGIONAL STRUCTURE

A connection between the jointing of the granite and the deformative movements responsible for the general structure of the surrounding rocks of the region is believed to be reasonably established. If the strain ellipsoid with assumed north and south stresses be applied to the strike of the vertical joints as shown in Figure 1, it will be seen that the directions of the planes of maximum shear in the bordering formations show close agreement with the fracture planes

[1] "The Vermillion Batholith," *Jour. Geol.*, Vol. XXXIII (1925), p. 481.

in the granite. This agreement is also in accord with the stretching criteria suggesting that north and south pressures were present during solidification of the magma. Hartman's law, indicating that for brittle substances the direction of greatest compressional stress bisects the acute angles of the joints, does not seem applicable here.

If the stresses were rotational, and this is clearly the case in the Kekequabic area as the drag folds and the fracture cleavage testify, the position of the strain ellipsoid and the position of the planes of maximum shear would apply equally well. The orientation of the ellipsoid would, in either case, lie with its longest axis in general parallel to the almost vertical dip of the bedding in the sediments, and its least axis at right angles to the trend of the folds.

RELATION OF FAULTING TO REGIONAL FOLDING

If in the preceding application of the strain ellipsoid to the joint fractures a correct analysis of the stress directions has been made, i.e., that major pressures were in directions north and south or slightly northwest and southeast, then confirmation of the interpretation should be looked for in the faulting. The strike of the faults should agree with the planes of maximum shear in the strain ellipsoid.

In Figure 1 several faults will be seen to agree with the directions of jointing in the granite. Also numerous chasms found in the granite and gabbro areas, and transverse lowlands cutting obliquely across ridges of the folded sediments, are suggestive of fault and joint valleys whose directions agree in general with those of the smaller joints. Many diabase dikes will also be seen to parallel these directions roughly. But, on the other hand, a very marked discrepancy is evidenced between the strike of the faults which offset the diabase dikes and the strike of the joints in the granite. If the strike of these faults be projected until they intersect, it will be seen that the bisectrices of the acute angles between them are normal to, rather than parallel with, the elongation of the granite and the trend of the regional folding.

The dikes are of Keweenawan age, or possibly much later, and the faults are later still. If the strain ellipsoid is now applied to these later faults which cut the diabase dikes, assuming that the fault planes represent directions of maximum shear, its elongation appears to be north and south. The dip of the dikes is practically verti-

cal, and the faulted segments indicate a shortening in directions more or less parallel to their strike. That is, they are thrust faults, and the pressures appear to have been from the east and west, or possible slightly north of east and south of west. In any event, whatever the direction of stresses that caused the faulting, it is certain that the faulting of the dikes occurred very much later than the tectonic movements that caused the regional folding, and that the discrepancy between the strike directions of these later faults and those of earlier faults and joints in the granite in no way invalidates the inferred connection between the primary structure of the Kekequabic granite and the regional structure of the surrounding sediments.

CONCLUSIONS

From the plotting of two sets of directional features impressed upon the Kekequabic granite during its plastic and solid stages, such as flow lines, schlieren, parallel orientation of crystals, faults, dikes, joints and small fractures, a definite relation is apparent suggesting movement of the magna from southwest to northeast, paralleling the trend of the regional folding of the intruded sediments. Movement from this direction is further indicated by the wide contact zone in the slates west of the granite, suggesting that the igneous rock underlies the sediments, and by the complex faulting in this area and the reversal of dip in horst blocks, suggestive of a drag by the eastward-moving magma. The absence of any granite bodies north and south of the main elongate mass, and the occurrence of several such masses of granite a mile or two east of the eastern end of the main mass, also suggests an east-west movement of the intrusion. Regional pressures north and south are definitely established by the closely compressed, vertically dipping sediments. All of the structural features in the granite are in accord with such directions of pressure, and the intrusion is believed to have been consequent upon the tectonic forces responsible for the regional folding and to have followed shortly the intense folding of the Huronian sediments. A larger mass of granite of the same peculiar composition as the Kekequabic intrusive, lying ten miles to the southwest, provides a source for the laterally moving satellite, which has all the appearance of being an offshoot from a larger plutonic magma.

THE MAJOR TERMS OF THE PRE-PALEOZOIC

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Correlation in pre-Cambrian geology is hampered by the confusion of its nomenclature and the failure of any terminology to secure world-wide application. How large this question looms is clear from Miss Wilmarth's recent publication, "The Geologic Time Classification of the United States Geological Survey Compared with other Classifications,"[1] of which more than half is devoted to the era and period terms of the pre-Paleozoic. This *Bulletin* is of high value in making the original definitions available in one book. The difficulties are partly matters of name and partly due to differences of opinion as to the interpretation of the evidence. The pre-Paleozoic rocks in most parts of the world include three chief divisions: a basal series of gneisses and coarse schists, an intermediate series which represents an altered stratified succession, and, at the top, a series of unfoliated sediments and associated igneous rocks.

There is no agreement as to whether these three divisions should be allocated to two groups or to three; and, if to two, whether the middle division should be united with the first or the last.

A classification into two groups, with the middle division joined to the uppermost, is adopted by G. A. Young[2] and S. von Bubnoff.[3] On the other hand, many authorities insist that the unconformity between the middle and the top divisions—the Eparchean interval—is one of the most fundamental in the geological record. Professor A. C. Lawson, indeed, would include the rocks above that unconformity in the Paleozoic.[4] The Archean is by no means devoid of sediments, and the fundamental nature of the Archean-Algonkian unconformity does not appeal to him nor to many Canadian geologists.

[1] *U.S. Geol. Survey Bull. 769*, 1925.

[2] *Trans. Royal Soc. Canada*, sec. 4 (1923), pp. 45–59.

[3] *Geol. Europa* (1926), pp. 4–5.

[4] *Congr. Geol. Intern.*, Vol. XII (1913), p. 370.

Considering the lithological differences of the three divisions there is much to be said for the adoption of three primary divisions in the pre-Paleozoic—a course followed by the Geological Survey of Canada, by Pirsson and Schuchert, *A Textbook of Geology* (1915), by Grabau, *Historical Geology* (1920), and by Coleman and Parks, *Elementary Geology* (1922), etc. The settlement of this problem is hampered by uncertainty as to the use of the major terms. For example, the term "Proterozoic" is used with three different meanings. Professor Howchin, in explaining the position of the early glacial deposits of South Australia, says that the trend of opinion is in favor of their being Proterozoic;[1] but as the term is used for the whole of the pre-Paleozoic and for the Upper pre-Paleozoic, and, as in Britain, for the Lower Paleozoic, calling this glaciation Proterozoic does not define whether its age is Cambrian or pre-Cambrian.

The terminology which has spread most widely in recent years is that due to Professor T. C. Chamberlin and Professor R. D. Salisbury, namely, Proterozoic for the Upper pre-Paleozoic, and Archeozoic for the Lower.[2] This arrangement has been adopted to some extent in Australia and South Africa. It has, however, found little acceptance in Europe and received no sanction in Britain, where Archeozoic has been used by some for the Upper instead of the Lower division of the pre-Paleozoic, and Proterozoic for the Lower Paleozoic. It may therefore be worth considering how this difference has developed, in the hope that it may lead to agreement in practice.

The dual use of Proterozoic existed in 1888. In the reports of the International Geological Congress held in London in that year, Lapworth made his customary use of Proterozoic[3]: "We know now, however, that like the Neozoic the Paleozoic is divisible into two grand life-periods—the Lower Paleozoic (or Proterozoic), and the Upper Paleozoic (or Deuterozoic), and that the collective sediments of each of these constitute three distinct rock systems." On page

[1] W. Howchin, "Geol. Barossa Ranges," *Trans. Royal Soc. S. Australia*, Vol. L (1926), p. 4.

[2] Chamberlin and Salisbury, *Textbook of Geology* (1906), Vol. II, p. 139.

[3] *Congr. Geol. Intern.*, Vol. IV (1888), p. 222, "Discussion—Classification du Cambrien-Silurien."

A54[1] is a statement which is abridged by Miss Wilmarth,[2] but in full is as follows:

> A division between the Laurentian and the Cambrian provisionally including the Huronian, Grand Canon, Llano, Montalban, and Taconic (of Hunt), Animikie, and other divisions shall be accorded a name different from any of them (such as Eozoic, Proterozoic, Eobiotic, Eomorphic, Agnotozoic, etc.), and allowing the greatest amount of liberty in the future, when it shall be determined whether the division shall be entitled to rank as one (or several), of the first order, having numerous subdivisions as above mentioned; or with or including any of the second order like the class Laurentian. No attempt shall be made at this time to prejudge this question and these names and this classification shall be regarded simply as the best that can be accomplished at the present time.

This statement is described as "expressing the preference of the majority of those American geologists whose opinions were ascertained." It shows that the minds of the American Committee were in a fluid state on nomenclature; their view was provisional and they did not sponsor Proterozoic in preference to the other terms quoted.

There existed then in 1888 the British use of Proterozoic by Lapworth, and an American proposal by S. F. Emmons which did not have the complete support of the Committee. Emmons in a letter to Persifor Frazer,[3] remarked:

> With Irving, Chamberlin, and Walcott I think that the Huronian, Keweenawian, and Grand Canon series, and whatever other clastic formations occur between the Cambrian and the Archean, should be included in one grand group of equivalent rank with the Archean, Paleozoic, etc., and since the term Paleozoic has by long use become so indelibly impressed upon geological classification that it would be difficult to give it up, I would suggest that the name Proterozoic should be given to this new group, signifying that its life was earlier than that of the other groups, without committing ourselves as yet to the statement that it was the first to appear upon the earth.

Lapworth, in rewriting the twelfth edition of Page's *Introductory Textbook of Geology* (published February, 1888), p. 152, says: "The Palaeozoic rocks fall very naturally in Britain into two main subdivisions: an earlier or Lower Palaeozoic, and a later or Upper

[1] *Idem*, "Report of the American Committee; The Archean," p. A54.

[2] *Op. cit.*, p. 32.

[3] *Congr. Intern. Geol.*, Vol. IV (1888), "Report of the American Committee," letter dated May 25, 1887, p. A71.

Palaeozoic subdivision. For the period in which the Lower Palaeozoic rocks were laid down the name Proterozoic (Greek *proteros*, the earlier, first), or earlier life, has been proposed, and to the Upper Palaeozoic the title of Deuterozoic (Greek *deuteros*, second), or second life." In the edition of 1899 the statement is similar except that as alternatives are given Proterozoic or Protozoic, and Deuterozoic or Deutozoic.[1]

Two points are clear from the original definitions. First, Emmons was desirous of redefining Paleozoic to include the upper pre-Paleozoic rocks, but realized that this course would not be adopted; and secondly, Lapworth states that the term Proterozoic "has been proposed" with his meaning. A letter from Professor W. S. Boulton, of Birmingham, who was a student under Lapworth and his successor there, informs us that Lapworth was using Proterozoic for the Lower Paleozoic in his lectures in 1886. The *Reports of the Congres Geologique International* for the fourth session were not published till 1891; but as R. D. Irving refers to Emmons's proposal,[2] Emmons appears to have priority of date of published use. British geologists have used Proterozoic for the Lower Paleozoic[3] since 1886, while as a term for the Upper pre-Paleozoic, though quoted by R. D. Irving in 1887,[4] it was rejected by him as it "seemed to fail in covering the ground sufficiently," and was apparently not used in America again until 1906. The conference of members of the United States Geological Survey on nomenclature held in 1889 adopted the terms Archean and Algonkian. Therefore, though Emmons has priority of date, Lapworth has priority in use. It cannot be said that Proterozoic was really in use in America as a term for the pre-Paleozoic until the publication of Chamberlin and Salisbury's *Textbook of Geology* in 1906.

Lapworth's use of the term has advantages. The prefix *proteros*

[1] *Intermediate Textbook* (1899), p. 188.

[2] *Amer. Jour. Science*, 3d series, Vol. XXXIV (1887), p. 373.

[3] E.g., Jane Donald, "On Some of the Proterozoic Gasteropoda . . . ." *Q.J.G.S.*, Vol. LVIII (1902), pp. 313–39; "Notes on the Genera Omospira, Lophospira, and Turritoma; with Descriptions of New Proterozoic Species," *Q.J.G.S.*, Vol. LXII (1906), pp. 552–72; Jane Longstaff (née Donald), "On the Genus Loxonema, with Descriptions of New Proterozoic Species," *Q.J.G.S.*, Vol. LXV (1909), pp. 210–28.

[4] *Amer. Jour. Science*, 3d series, Vol. XXXIV, p. 373.

means earlier. The opinion is spreading that the horizon between the Silurian and the Devonian is the most important break in Paleozoic life. Lapworth's subdivision of the Paleozoic into two sections each of three systems is likely to be increasingly adopted; and his terms may be clung to the more firmly as Proterozoic would be the suitable name for the "earlier" of these two divisions.

The designation of the upper part of the pre-Paleozoic as "earlier" is less attractive; the term would be appropriate to the whole of the pre-Paleozoic as it is used by the United States Geological Survey according to Miss Wilmarth,[1] but it is hardly suitable if it is to follow Archeozoic. Archaic life, earlier life, old life is not a satisfactory order. Hence it is not surprising that Lapworth's many disciples in Britain adhere to his meaning. Since questions of meaning and priority were involved, it is surprising that the United States Geological Survey did not in 1907 use Sedgwick's term Protozoic. It is true that Lapworth had used Protozoic just as he used the shortened form Deutozoic as alternatives, but Professor Boulton tells us that Lapworth did not regard them as satisfactory.

The use of the term Archeozoic for the lower division of the pre-Paleozoic is a reversal from its first meaning, as it was proposed in 1872 by J. D. Dana[2] as a substitute for Azoic because the rocks supposed to be Azoic were found to afford traces of the simplest forms of life. It is clear that Dana regarded it as applying only to the upper part of his Archean.[3] He had previously[4] shown that in his view there was only one pre-Paleozoic era, namely the Archean: "There is no room for another grand division between Archean and Paleozoic any more than for one between Paleozoic and Mesozoic."

Archeozoic is the period of archaic life, which should be more primitive than that of the Paleozoic; and the term is suitable to those obscure traces of life found in the Torridonian of Scotland and in the Beltian of America, and to the fauna of the Steep Rock series. The term is more appropriate to the unfoliated sediments with obscure traces of life at the end of the pre-Paleozoic than for the coarse holocrystalline basal gneisses of Canada and Scotland in which there

[1] *Op. cit.*, p. 42.
[2] *Corals and Coral Islands*, Appendix, p. 373.
[3] *Manual of Geology*, 4th ed. (1895), pp. 404–13, 440–53.
[4] *Amer. Jour. Science*, 3d series, Vol. XLIII (1892), pp. 460–61.

is no direct evidence of life, though life might have had its dawn during their formation.

Appropriate names for the successive stages in the development of life through the dawn of life, archaic life, ancient life, and middle life to recent life would be Eozoic, Archeozoic, Paleozoic, Mesozoic, and Kainozoic.

Many terms have been proposed for the pre-Paleozoic as a whole. Increase of knowledge has rendered some inappropriate while others have been used with several different meanings.

Agnotozoic was suggested in 1887 by R. D. Irving to cover all the fragmentary rocks between the base of the Cambrian and the summit of the Archean.[1] It has been adopted by different writers, notably by Haug.[2] The case against it may be put in Sederholm's words:[3] "But as I have pointed out before, this word implies a *contradictio in adject*, the organisms being either wanting, in which the group is not zoic, or existing, in which case the term *agnotus* is not justified."

Azoic was introduced by Murchison,[4] and it included the whole of the pre-Paleozoic. It has received much support both in Europe and in America from authors of repute such as d'Orbigny, Page, Dana, Von Zittel, and Schuchert. Its meaning, "without life," suggests that it should be restricted to igneous rocks or the highly specialized application of Dana and Schuchert.[5]

Collozoic was proposed by A. C. Lane (Greek *kolla*, "glue," and *zoe*, "life," meaning soft-bodied or gelatinous.[6] The time included in it is not a common subdivision, for it begins with the Grenville and ends at the top of the Animikie, leaving the Keewatin and Coutchiching to his Azoic. The value of the term lies in the fact that it stresses the soft-bodied character of the organisms, but it has been entirely neglected since its introduction in 1917. It could be extended from its meaning to cover the whole of the pre-Paleozoic.

[1] *Amer. Jour. Science*, 3d series, Vol. XXXIV (1887), p. 373.

[2] *Traité de Geologie*, tome II, p. 566.

[3] *C. R. Congr. Geol. Intern.*, 12th session (Toronto, 1913), pp. 383–84.

[4] *The Geology of Europe and the Ural Mountains* (1845), p. 10.

[5] *Textbook of Geology*, 2d ed., Vol. II (1924), p. 103.

[6] *Amer. Jour. Science*, 4th series, Vol. XLIII (1917), p. 46.

Eobiotic and Eomorphic are quoted by Miss Wilmarth as proposals by C. H. Hitchcock,[1] but they are not included in the *Compte Rendu* of the London meeting published in 1891. They are derived from the Greek *eos*, "dawn," and *biotikos*, "pertaining to life," and *morphe*, "form." While the terms are in the same category as Collozoic in that they are descriptive, they were partly based on the mistaken belief that the Huronian beds were the first to show any signs of sedimentation. The terms apparently have not been used except by them.

Eozoic was coined by Sir J. W. Dawson after the discovery of *Eozoon canadense*. It included the Huronian and Laurentian of these days.[2] The term is derived from the Greek *eos*, "dawn," and *zoe*, "life," and is consequently descriptive of one period in the early history of the earth. This is true whatever view is held on the subject of *Eozoon*, as was clearly understood by A. Winchell, who said: "Eozoic, unlike Azoic (formerly employed), can never become inapplicable through the progress of discovery."[3] This statement is still valid and the name is in conformity with the succession of life-periods. Unfortunately Eozoic has been used in a variety of ways, ranging from the whole to different sections of the pre-Paleozoic and to hypothetical eras before the pre-Paleozoic. The widespread use of the term Eozoic shows its usefulness.

Hypozoic, on the other hand, is another word which has been used only by its founder. It is derived from the Greek *hupo*, "below," and *zoe*, "life," and was due to J. Philips.[4] It would be difficult to define its upper limit and it could be regarded only as a synonym of the specialized use of Azoic.

Progonozoic or Progonic were introduced at the International Geological Congress of 1913 in Toronto, when an attempt was made to introduce some order and unanimity into the nomenclature of the pre-Cambrian. Sederholm, when criticizing Irving's term, "Agnotozoic," suggested Progonozoic or Progonic for the group of ancestral

[1] *Internat. Geol. Congr. American Committee Reports* (Philadelphia, 1888), p. A14; P. Frazer, reporter.

[2] *Acadian Geology*, 2d ed. (1868), p. 658.

[3] *Geological Studies or Elements of Geology*, 3d ed. (1889), pp. 361–69.

[4] *Manual of Geology* (1855), pp. 76–89.

organisms. He suggested the further subdivision into Neo-Progonic, Meso-Progonic, and Archeo-Progonic. The criticism which Van Hise applied to the similar subdivision of the term Proterozoic by F. D. Adams seems to be equally applicable here, namely, that it implies three distinct life-periods which cannot be recognized in the rocks. At the same time Sederholm's contentions are valuable from his plea for the principles of good word-building.

Proterozoic has already been noticed. Protozoic was introduced by Sedgwick[1] for use in case the pre-Cambrian should yield fossils; but Lapworth used it in a different sense, though with some degree of misgiving. Prozoic was proposed by J. Philips[2] and was preferred by Endlich[3] because of the great ease in defining it.

There are then in existence twelve different terms covering all or parts of the same set of rocks. Nearly all express the ancestral character of the life of the time, and have points to recommend them, but most of them have lost value because of this varied application. A suitable term to be appropriate to the pre-Paleozoic should express the position of that division of time in the geological sequence and the ancestral nature of its life. We have then to bear in mind the principles of good word-building, so that the sequence may be preserved, and at the same time endeavor to express this ancestral quality. We have also to remember the British objection to the change in the use of Proterozoic. None of the existing words is free from objection, with the possible exception of Collozoic. So one of us has added another name to the list, by using the term Pampaleozoic,[4] from the Greek word for primeval. It is a zoic form and is applicable to the primitive conditions before the Paleozoic. The chain of life has passed through the stages of primeval life, old life, middle life, and recent life, or Pampaleozoic, Paleozoic, Mesozoic, and Kainozoic.

The nomenclature of stratigraphical geology is not determined by arbitrary obedience to priority, and established usage counts for more in the position of a term than literal correctness. If there were

[1] *Proc. Geol. Soc. London*, Vol. II, No. 58 (1838), p. 684.

[2] *Manual of Geology* (1855), p. 624.

[3] *U.S. Geol. and Geog. Survey Terr., Tenth Annual Report* (1878), p. 103.

[4] Harmsworth, *Universal History*, Vol. I, p. 80.

good prospects of the general adoption of Proterozoic for the lower and Archeozoic for the upper division of pre-Paleozoic time, it would no doubt be well for pre-Cambrian geology for those terms to be accepted. Respect, however, for the memories of Dana and Lapworth may cause reluctance to use terms which they invented in senses opposite to the original meanings. The advantages of a uniform major nomenclature for the pre-Paleozoic rocks are, however, so great that probably most geologists would be ready to accept any compromise that seemed likely to find general acceptance.

EDITORIAL

THE WORK OF WELLER

Stuart Weller laid a broad foundation carefully oriented and firmly based and was building a noble structure upon it when the trowel fell from his hand. Our only consolation lies in the hope that younger hands trained to his method and inspired by his spirit will complete the work so well begun. The researches of Weller centered on the Paleozoic problems of the great interior basin of North America, perhaps the most symmetrical expression of early stratigraphic and faunal evolution presented by our planet. Weller came to the field as by the decree of destiny. Born on its eastern border, reared in its midst, and catching his early inspiration from it, he chose for his collegiate and technical training an institution seated on the eastern emerging edges of the Paleozoic terranes where they repose on the Adirondack nucleus and where the Nestor of American paleontologists laid the foundation of our stratigraphy and gave it nomenclature. Thus prepared, he was called to a seat of learning and of research in the heart of the broad Paleozoic field where he enjoyed an atmosphere of sympathetic companionship in inquiry. Here his workshop was amid the boxes of the unworked riches of the great Paleozoic collections of Hall and Gurley. For the training of students he chose a rare spot on the banks of the Mississippi, rich in physical and biological problems. By the generosity of one who had received inspiration from him, this became in later years a permanent possession, specially equipped for comfort and service, and there his close contact with a loved phase of nature and with younger eager minds gave him great satisfaction.

His independent personal research was enhanced by calls to critical work from official surveys both east and west which sought his skill and good judgment in the solution of their Paleozoic problems. This gave him opportunity to broaden his personal observations and to deepen his insight.

In his last years his chief work was concentrating upon the notable culmination of marine animal life which immediately preceded its retreat from the interior basin to make way for the climax of plant life which closed the Paleozoic era.

Early in his work he had made a notable contribution to the intercontinental relations of Paleozoic life. His studies disclosed the notable fact that certain distinctive faunal forms appeared in Iowa closely following their appearance in the Baltic region, while it was only later that these forms migrated eastward into the New York embayment. This early triumph in a difficult field gave promise of great things when, in the fullness of his studies and the ripeness of his judgment, he should return to the study of intercontinental migrations. On this expected return some of us had set high hopes and fond expectations. His mature conclusions would have had peculiar value because of the breadth of his knowledge, his great care and conscientiousness, his unsparing industry, and his sound habits of thought. The loss of this anticipated contribution is irreparable.

T. C. C.

REVIEWS

Die Geologie und die Salzdome im südwestlichen Teile des persischen Golfes. By R. K. RICHARDSON. Verhandl. d. Naturhist. Medizin. Vereins zu Heidelberg, N. F., Bd. XV, 1926. Pp. 49, figs. 6, sections and maps.

The data of this paper are from the work of the writer and his assistant in Persia for the Anglo-Persian Oil Company, Ltd. On account of the almost complete absence of vegetation, the geological structure stands out with exceptional clearness and completeness.

The stratigraphic section is as follows:

Quaternary:	
Alluvium, sand, and very fine sandy clay	
Tersai Series, coarse friable sandstones, limestones, conglomerates	100–150 m
Tertiary:	
Neogene—Fars Series:	
Upper Fars Beds, sandstones and limestones with intercalated green marls and sandy clays	1,000 m.
Middle Fars Beds, limestones, marls and marly clays	200 m.
Lower Fars Beds, massive gypsum	450 m.
Oligocene:	
Khamir limestone, thick massive very fossiliferous nummulitic limestone	200 m.
Eocene:	
Khamir Marl	
Upper, or Micropsis beds, shales	150 m.
Lower, marls and marly limestones with a few very nummulitic beds	500 m.
Mesozoic:	
Upper Cretaceous	
Rudistes limestone, mostly hard limestone with marly Rudistes in the upper part	370 m.
Tectonic contact:	
Pre-Upper Cretaceous	
Hololocrystalline igneous rocks, granites, syenites, quartz, deorite, intrusive into the Hormuez Series	
Hormuez Series	

Upper, chiefly gypsum with effusive rocks, tuffs, and agglomerates
Middle, mostly granular dolomitic limestone with anhydrite
Lower, bedded rock salt
Khamir Group
Crystalline schists, black and white limestone, stinking limestone. The relations of this group were not clear

The salt domes mapped are eight in number and lie on the mainland, in or near the coast and on islands in the Gulf. Other salt domes are known to exist both on the mainland and on other islands in the Gulf. The salt domes are circular to oval in plan, have diameters ranging from 5 to 10 km., and commonly are in the axes of anticlines. On five of the domes the salt has completely pierced the overlying beds and in some places slightly overturned them. The Tersai beds of the Quaternary are involved in the upthrust on the Kishm Island dome. On account of the relief and of the lack of vegetation the upthrust of the salt with the concomitant sharp upturning of the adjacent edges of the flank beds is apparently revealed with the clearness of a textbook diagram. The whole Hormuez series has been irrupted into its present positions. The Upper and Middle Hormuez beds in some way look comparable to the cap rock of the American salt domes. The upthrust of the Hormuez series amounts at least to 3,600–2,900 meters (8,700–9,700 feet).

Orogenically, the salt-dome area of Persia lies within the zone of the Zagros arch of the Alpinohimalayan Mountain system. The mountain systems of Persia in general have a northwest strike, but in the salt dome area the trend is west-northwest to east-west. Throughout Persia the period from the Upper Cretaceous into the Neogene was one of great geologic tranquillity; faint deformation took place in the early Miocene and strong deformation in two periods of the later Neogene. In the Gulf Coast region the deformation came in Fars time (late Pliocene) and reached its maximum before the deposition of the Tersai Beds (Pleistocene), but persisted long enough slightly to involve those beds. The formation of the salt domes was contemporaneous with these orogenic movements, did not take place before the end of the Pliocene, and persisted partially into the Quaternary.

The salt domes are plainly the result of the upthrust of plastic sedimentary formations. No data were observed that were contrary to Stille's theory of the origin of salt domes by the plastic yielding and flowing of a sedimentary salt series—in this case a salt-anhydrite-gypsum-pyroclastic series—under orogenic deformation. Although there has been much igne-

ous activity in the area of the salt domes, there is no evidence for any causal connection between it and the formation of the salt domes; the igneous activity ceased before the deposition of the Rudistes limestone in the Upper Cretaceous, and the upthrust of the salt domes did not come until the end of the Pliocene.

DONALD C. BARTON

Map of the Mineral Deposits of the World, prepared by the Prussian Geological Survey (Dietrich Reimer, Ernst Bohsen). Berlin, 1927.

This map will be heartily welcomed by students of ore deposits and of economic geography. It consists of two maps of four sheets each, each map covering a hemisphere with a scale of one to fifteen million. Accompanying the maps is a text consisting of 312 pages of mineral statistics arranged, not only by countries, but, where data were available, by states within countries. In these tables every locality as shown on the map is identifiable by a number. Geological horizon, the character of the deposit, the content by percentage and useful materials, and the production by quantity for the year 1913 and the latest available year is given. On the maps the legends are in French, German, English, and Spanish. By symbols are indicated the class of deposits, for example, sedimentary or contact-metamorphic, geologic age, the kind of material, its relative economic importance, and whether the deposit is active or idle, this large variety of information being made visible by an ingenious combination of symbols, colors, and numbers. When mounted, each map is approximately 5×6 feet. The map makes readily possible a rapid survey of the mineral resources of the world.

E. S. B.

The Mesozoic Stratigraphy of Alaska. By GEORGE C. MARTIN. *U.S. Geol. Survey Bull. 776*, 1926. Pp. 493; figs. 13.

The Mesozoic strata of Alaska are of great importance for many reasons. They show significant relations with known sections in other regions, and they constitute one of the most extensive and complete sections of the Mesozoic in North America. The most extensive metallization in Alaska accompanied the intrusions of Jurassic and Cretaceous times. The best-known oil-bearing formation is of Mesozoic age. Valuable coal deposits also occur in the Mesozoic.

The bulletin is divided into three sections, one for each of the periods of the Mesozoic. Each section includes general discussions of areal occurrence, stratigraphic sequence, correlation, and geologic history, as well as detailed regional descriptions. For each of the regional descriptions there is a historical review of previous work, a stratigraphic description, and a discussion of age and correlation, together with lists of fossils. The field location of each collection of fossils is given.

This bulletin is of great value, not only because it fills out American stratigraphy in the place where it is most deficient but also because it summarizes and makes available all previous work. Many of the stratigraphic descriptions are new, being based on the author's field observations, and many of the lists of fossils have not hitherto been published.

A. B. S.

Laterite-Material and Attempt at a Geologic Evaluation. By HERMANN HARRASSOWITZ. *Fortschritte der Geologie und Palaeontologie*, edited by W. Soergel, Breslau. Berlin: Gebrueder Borntraeger, 1926. Pp. vi+311; text figs. 43; pls. 1.

In this remarkable piece of work the author has attempted to bring together the existing knowledge regarding the occurrence and origin of laterite and to present in a new light this important subject, substantiated by complete chemical analyses of laterite profiles. To make the argument more convincing the kaolinite problem has been discussed preliminary to the treatment of laterite.

The aluminous alteration products are separated into siallites, including kaolinite and allophanite (hydrous aluminium silicates) and into allites, including beauxite and laterite (hydrates of alumina). From the literature and from the analyses of complete laterite profiles, the conclusion is drawn that a migration of the dissolved materials takes place. These materials are deposited in various places in the profile, especially near the surface, where thus not only an enrichment of iron and alumina hydrates occurs, but also an enrichment of hydrous aluminium silicates. In the lower zones of the profiles a belt of kaolinitization can be observed, but more commonly bands of siallite formations appear. Kaolinitization in sheet-like structures may develop during the process of weathering only in laterite profiles. Laterite originates during changing climates and greatly influences vegetation.

A study of the weathering of "podsol" (acidic fuller's earth) definitely shows that kaolinite is not formed; consequently kaolinite on which coal

has been superimposed could not have originated thus. These deposits appearing to be kaolinites are laterites degraded by overlying bogs; thus the occurrence of iron sulphides and carbonates can easily be accounted for in kaolinites which have no connection with the formation of siallites. Free alumina may be produced through the process of laterization as well as through other processes.

Fossil laterites often show distinct profiles and are principally found in the Carboniferous and Tertiary formations. Some, however, are to be noted in the Cretaceous; fewer in the Jurassic, Triassic (where they never occur in connection with red beds), and in the Permian. The frequent occurrence of coal superimposed on laterite may occur equally well during changing climates. The formation of both is partly dependent upon times of relative quiescence which are morphologically distinguished by flat surfaces and land-locked seas. In such areas laterites, being poor in alkalies, also act as preservers of humus. Similar conditions can be assumed for Carboniferous times. Laterite is formed in dry inland regions, in proximity to red beds and especially where the process of silicification is in operation. The climate of the period, however, is not to be inferred from the presence of bogs. Evergreen and similar forests depending upon abundant precipitation were hardly possible in a region where laterite was developing. Both early and late Tertiary times were characterized by a tropical laterite climate, as is revealed by a study of the plant and animal kingdoms of this period. This book should prove of much value to geologists.

W. A. W.

Bibliography of the Geology of Oregon. By DOROTHY E. DIXON. *University of Oregon Publication.* Geology Series, Vol. I, Eugene, Oregon, 1926. Pp. 125.

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R. T. C.

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